CALIFORNIA ENERGY COMMISSION

Skylight Photometric and Thermal Reports

Construction and Calibration of Skylight Photometric Test Facility (product 5.3.5)

Photometric Testing Lessons Learned (product 5.3.2a)

Skylight Test Chamber Design Report: Skylight U-Factor Tests (product 5.3.2a)

Summary of U-Value Test vs. Model (product 5.3.2b)

Summary of SHGC Test vs. Model (product 5.3.3b)

Skylight Visible Properties Research (product 5.3.4)

Summary of VLT Angle Test vs. Model (product 5.3.4b)

TECHNICAL REPORT

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Gray Davis, *Governor*

CALIFORNIA ENERGY COMMISSION

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Heschong Mahone Group, Inc.: Principal in Charge: Lisa Heschong. Project Director: Jon McHugh. Project staff: Puja Manglani and Rocelyn Dee.

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

This document is one of 33 technical attachments to the final report of a larger research effort called *Integrated Energy Systems: Productivity and Building Science Program* (Program) as part of the PIER Program funded by the California Energy Commission (Commission) and managed by the New Buildings Institute.

As the name suggests, it is not individual building components, equipment, or materials that optimize energy efficiency. Instead, energy efficiency is improved through the integrated design, construction, and operation of building systems. The *Integrated Energy Systems: Productivity and Building Science Program* research addressed six areas:

- Productivity and Interior Environments
- Integrated Design of Large Commercial HVAC Systems
- Integrated Design of Small Commercial HVAC Systems
- Integrated Design of Commercial Building Ceiling Systems
- Integrated Design of Residential Ducting & Air Flow Systems
- Outdoor Lighting Baseline Assessment

The Program's final report (Commission publication #P500-03-082) and its attachments are intended to provide a complete record of the objectives, methods, findings and accomplishments of the *Integrated Energy Systems: Productivity and Building Science Program*. The final report and attachments are highly applicable to architects, designers, contractors, building owners and operators, manufacturers, researchers, and the energy efficiency community.

This attachment, "Skylight Photometric and Thermal Reports" (Attachment A-27), provides supplemental information to the program's final report within the **Integrated Design of Commercial Building Ceiling Systems** research area. It includes the following reports:

1. **Construction and Calibration of Skylight Photometric Test Facility.** Describes the method and equipment used to measure the photometric properties of skylights and their light wells in the same format used to characterize electric lighting luminaires.

2. **Photometric Testing Lessons Learned.**

3. **Skylight Test Chamber Design Report: Skylight U-Factor Tests.** Describes how a U-factor test facility was constructed and calibrated for the purpose of characterizing the thermal conductance properties of skylights with and without their light wells.

4. **Summary of U-Value Test vs. Model.** Results of skylight U-factor testing.

5. **Summary of SHGC Test vs. Model.** Results of skylight solar heat gain coefficient testing

6. **Skylight Visible Properties Research.** Describes methodology and results of study that characterized how skylight shapes, glazing types and light well configurations affect visible optical characteristics.

7. **Summary of VLT Angle Test vs. Model.** Results of skylight visible transmittance testing.

The Buildings Program Area within the Public Interest Energy Research (PIER) Program produced these documents as part of a multi-project programmatic contract (#400-99-413). The Buildings Program includes new and existing buildings in both the residential and the non-residential sectors. The program seeks to decrease building energy use through research that will develop or improve energy efficient technologies, strategies, tools, and building performance evaluation methods.

For other reports produced within this contract or to obtain more information on the PIER Program, please visit www.energy.ca.gov/pier/buildings or contact the Commission's Publications Unit at 916-654-5200. All reports, guidelines and attachments are also publicly available at www.newbuildings.org/pier.

ABSTRACT

The “Skylight Photometric and Thermal Reports” attachment is a set of seven reports produced by the Integrated Design of Commercial Building Ceiling Systems project. This was one of six research projects within the *Integrated Energy Systems: Productivity and Building Science* Program, funded by the California Energy Commission’s Public Interest Energy Research (PIER) Program.

In the past, skylights for commercial buildings are rarely tested for their light transmittance, heat transfer, and solar gain characteristics, and little data exists about their performance. This makes it difficult to specify skylights based on an objective standard and to model their performance in real buildings. This research project developed testing methodologies and conducted controlled tests to characterize the thermal conductance, solar heat gain, and visible light transmittance of skylights that represent typical commercial installations. The detailed results are published in the program’s final report (Commission publication #P500-03-082), and in the “Design Guidelines for Skylights with Suspended Ceilings” produced as part of this research project.

This attachment includes seven background research documents that supplement the final report and Design Guidelines. Among the key research findings is the conclusion that light wells reduce solar heat gain. The testing resulted in new data on effective visible transmittance and U-factor that will likely influence skylight rating and simulation methods.

Authors: Jon McHugh, Heschong Mahone Group; Sam Yuan, ETC Laboratories, Inc.; David Tait, Tait Solar Co.

Keywords: skylight, light well, daylighting, solar heat gain, SHGC, U-factor, visible transmittance, commercial building ceiling, thermal conductance, suspended ceiling

Integrated Energy Systems Productivity & Building Science Program

A project of the State of California PIER Program

Construction and Calibration of Skylight Photometric Test Facility

Final Report for Task 5.3.5a Skylight Photometry Lab and Calibration

January 21, 2002

Integrated Design of Commercial Building Ceiling Systems/Jonathan McHugh

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1.1. Preface

The HESCHONG MAHONE GROUP has produced this report as part of the Integrated Design of Commercial Building Ceiling Systems research element of the *Integrated Energy Systems - Productivity and Buildings Science* energy research program managed by the New Buildings Institute. Peter M. Schwartz is the Senior Program Director of this project for the New Buildings Institute. Cathy Higgins is the Program Director of this project for the New Buildings Institute.

The *Integrated Energy Systems - Productivity and Buildings Science* program is funded by the California Energy Commission under Public Interest Energy Research (PIER) contract No. 400-99-013. The PIER program is funded by California ratepayers through California's System Benefit Charges and is administered by the California Energy Commission (CEC). Donald J. Aumann is the CEC Programmatic Contact.

1.2. LEGAL NOTICE

1.3. Acknowledgements

This report was prepared by Jonathan McHugh at the HESCHONG MAHONE GROUP with assistance from Ian Lewin, Jim Walker and Jim Domigan at Lighting Sciences Inc.

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CrystaLite Inc.,	**DayLite Natural Lighting Technologies LLC**
Naturalite Skylight Systems,	**Sunoptics Prismatic Skylights**
TriStar Skylights	**Velux**

The Skylight Testing Technical Advisory Committee gave important feedback on the design of the research and the format of the results.

Members of the Skylight Testing Technical Advisory Committee are:

Dave Alexander, Sears; Dariush Arasteh, LBNL; Ian Ashdown, byHeart Consulting; Morad Atif, National Research Council Canada; Bill Beakes, Armstrong World Industries; Bob Berger, Independent Testing Laboratories; Gus Bernal, Day Lite Company; Jim Blomberg, Sunoptics Prismatic Skylights; Dan Cherney, CPI; Doug Cole, Micron Vinyl; Andre Desjarlais, ORNL; Neall Digert, Solatube; David Dilaura, University of Colorado Boulder; William duPont, LBNL; Charles Ehrlich, HESCHONG MAHONE GROUP; Hakim Elmahdy, National Research Council Canada; Stuart Feldman, Discrete.com; Sean Flanigan, Wasco Products; Steve Harrison, Queen's University; Joe Hayden, Pella Windows; Randy Heather, Naturalite Skylight Systems; Richard Heinisch, Lithonia Lighting; Lisa Heschong, HESCHONG MAHONE GROUP; Ivan Johnson, TriStar Skylights; Joe Klems, LBNL; Eleanor Lee, LBNL; Lance Livingston, Lighting Technologies; Peter Lyons, Australian Window Association; Ross McCluney, FSEC; John Mors, Day Lite Company; Brad Prouty, California Daylight; Steve Richter, CrystaLite Inc.; Francis Rubinstein, LBNL; Todd Saemish, Lighting Analysts; Stephen Selkowitz, LBNL; Bipan Shah, D&R International; Roland Temple, Velux; Martin Timmings, Canlyte; Stephen Treado, NIST; and Randy Van Horst, Quality Testing.

1.4. Foreword

Approximately 75% of new retail construction makes use of dropped ceiling systems (T-bar and acoustical tile). Acoustic ceiling/lighting design affects fire protection, seismic safety, lighting, daylighting, insulation, mechanical systems and acoustics. Electric lighting accounts for over one third of all commercial electricity consumption, and over one quarter of peak demand for commercial buildings and 11% of peak demand for all uses in California! At least 60% of ceiling area is directly below a roof and therefore, how well building components and energy consuming systems are integrated to configure the ceiling system is a serious issue that impacts the resultant building energy use.

The purpose of this research element is to develop a protocol for designing and specifying highly efficient ceilings that will incorporate effective placement of insulation, daylighting via toplighting and daylight-responsive electric lighting controls. This protocol will help to reduce uncertainty regarding code compliance and construction costs.

This research in this report has been designed to support of the Integrated Design of Commercial Building Ceiling Systems research element. This research project consists of three related components:

1. Effectiveness of lay-in insulation
2. Comprehensive skylight testing
3. Culminating in an integrated ceiling system protocol for quality lighting (including daylight) and energy savings.

This report describes how a photometric test facility was constructed and calibrated for the purpose of characterizing the photometric properties of skylights with and without their light wells.

1.5. Abstract

This report describes the methods and equipment used by Lighting Sciences Inc. to measure the photometric properties of skylights and their light wells in the same format used to characterize electric lighting luminaires. Angular intensities from the base of the light well were measured using a Type C goniometer. The size of the goniometer was minimized by using mirrors to "fold" the paths of light and by measuring one quadrant of the base at a time and recombining the results mathematically.

In addition to describing the physical construction of the goniometer, this report describes the results of calibration measurements to assure that the values recorded by this instrument are accurate within acceptable limits. Photometric sensors were calibrated relative to a NIST traceable standard lamp. To assure that sensors are correctly reading the intensity of an area source, candela distribution measurements were taken on a two foot by two foot square luminaire in the skylight photometer and compared to similar measurements on a standard mirror photometer. The results on the skylight photometer were within 3% of those on a standard luminaire testing photometer.

2. INTRODUCTION

Goniometric testing of light sources characterizes the angular distribution of light intensities from a source. When this information is stored in a standardized photometric file format such as IES LM63-1995[1], lighting design software programs can predict how the measured source will light a space. Most luminaires specified for commercial buildings in the United States have photometric files that result from goniometric testing.

Skylights rarely have any tested photometric information available. Unlike light fixtures, which require only one photometric test, skylights require a separate test to characterize their performance at each significantly different sun angle as well as a separate measurement for overcast conditions. If photometric files for skylights were available, we could predict how skylights would make a space look, better understand how much lighting energy they displace and make informed decisions on which skylight performs better.

This Public Interest Energy Research (PIER) project is testing a variety of skylights with different shapes, materials, and on a variety of light wells to help understand how these factors influence the distribution of light into the occupied areas below.

Most light fixtures are tested under conditions known as "far field" photometry. The light fixtures can be treated as essentially a point source of light without excessive error as long as the measurements are taken from a distance. The minimum distance usually used for this type of photometry is 5 times the largest dimension of the source being measured. For our skylight wells and rectangular fixtures, the longest dimension is the diagonal.

Since the diagonal across the base of our 4 ft by 4 ft (plan dimensions) light well is 5.6 ft, using the "5 times" rule, far field photometry is typically measured 28 feet away. Thus commonly held practice would assume that a test chamber with a 28 ft height and a 28 ft diameter would be needed to test a 4 ft by 4 ft skylight.

Lighting Sciences Inc. (LSI), the testing subcontractor, developed a test methodology and apparatus that would fit in a 17-ft tall cube. This substantially reduces the real estate and thus costs associated with testing skylights. A more affordable test method translates into a test method that industry is more likely to adopt.

This report describes the design, construction and calibration of the LSI skylight goniometer.

[1] IES LM-63-1995, IESNA Standard File Format for Electronic Transfer of Photometric Data, New York, NY 1995.

3. SCOPE OF TESTING AND REPORTING

The PIER skylight testing project selected four foot by four foot skylights as this was the smallest size of skylight that one would typically find on a commercial building. In addition, there are some skylight types that we wanted to test that are not made in a smaller size - most notably the compound parabolic shaped skylights.

Recognizing that the luminous performance of skylights is a product of the skylight and the light well beneath the skylight, the project tested skylights in combination with different light wells. Table 1 lists the combinations of skylights and light wells tested. These combinations were selected to specifically identify the effect of different modes of diffusion (pigment, fibers, and refractive shapes) on the distribution of light under skylights and their light wells. Light well depth, surface properties and presence of bottom diffuser were varied to investigate the effect of these elements. Since the focus was on skylights used on commercial buildings in California's mild climate, many of the skylights were single glazed.

Table 1: Tested skylight/lightwell combinations

Test No.	Material	Shape	Color	Glazing(s)	Tilt	Well Ht.	Well Surfa	Diffuser	Rotation
1	Glass	Flat	Clear	Double w/ low-e	Horz.	1'	Diffuse	No	
2	Glass	Flat	Clear	Double w/ low-e	Horz.	3'	Diffuse	No	
3	Glass	Flat	Clear	Double w/ low-e	Horz.	6'	Diffuse	No	
4	Glass	Flat	Clear	Double w/ low-e	Horz.	6'	Diffuse	Yes	
5	Acrylic	Dome	White	Single	Horz.	1'	Diffuse	No	
6	Acrylic	Dome	White	Single	Horz.	3'	Diffuse	No	
7	Acrylic	Dome	White	Single	Horz.	6'	Diffuse	No	
8	Acrylic	Dome	White	Single	Horz.	3'	Specular	No	
9	Acrylic	Dome	White	Single	Horz.	6'	Specular	No	
10	Acrylic	Dome	White	Single	Horz.	3'	Specular	Yes	
11	Acrylic	Dome	White	Single	Horz.	6'	Specular	Yes	
12	Acrylic	Dome	White	Double	Horz.	1'	Diffuse	No	
13	Acrylic	Compound Arch	Clr. Pris.	Double	Horz.	1'	Diffuse	No	
14	Acrylic	Compound Arch	Clr. Pris.	Double	Horz.	6'	Diffuse	No	
15	Acrylic	Compound Arch	Clr. Pris.	Double	Horz.	1'	Diffuse	No	90 deg
16	Fiberglass	Pyramid	Crystal/crystal	Panel	Horz.	1'	Diffuse	No	
17	Fiberglass	Pyramid	Crystal/crystal	Panel	Horz.	6'	Diffuse	No	
18	Polycarbonate	Pyramid	Clear	Twinwall	Horz.	1'	Diffuse	No	
19	Polycarbonate	Pyramid	Clear	Twinwall	Horz.	6'	Diffuse	No	
20	Acrylic	Pyramid	Bronze	Single	Horz.	3'	Diffuse	No	
21	PET	Compound Arch	White	Single	Horz.	1'	Diffuse	No	
22	PET	Compound Arch	White	Single	Horz.	1'	Diffuse	No	90 deg

For each of the 22 skylight/light well combinations under clear skies, a photometric test was to be performed for each 10 degree increment in solar elevation from sunrise to sunset as well as a test at solar noon. These tests were performed in the summer to maximize the number of sun angles tested. Clear skies were defined as having a sky ratio less than 25%. The sky ratio is defined here as the ratio of diffuse horizontal illuminance to total horizontal illuminance. A single overcast sky test was also required for each of the skylight/lightwell combinations. An overcast sky was defined as having a sky ratio greater than 85%.

For each test, the test lab provides the raw data from the tests, photometric files in IESNA LM 63-1995 photometric file format and standard photometric reports from each of the photometric files. This data set provides detailed photometric information on many of the skylight types installed on commercial buildings in California.

4. DESCRIPTION OF TEST EQUIPMENT

4.1. Rationale for Photometer Design

In order to maximize the portion of funding available for actual testing, costs associated with building space rental need to be reasonable while not compromising test accuracy. A difficulty in achieving this relates to test distance: a four by four foot skylight has a diagonal dimension of 5.66 feet. In order to meet the requirements of IESNA LM41, the distance from the center of the test item to the photocell should be 5 times this dimension, or 28 feet.

It is worth noting that the IES 5x rule creates an acceptable tolerance of 1% *for diffuse fixtures*. For fixtures which may have steep gradients in their candlepower distribution, tolerances due to the test distance might exceed 1%. (Ref. LM41). LSI feels that the 5x rule should not be compromised, particularly as the skylight candlepower distributions are unknown at this time. We have therefore made considerable effort in reviewing photometric test systems, which allow adherence to the IES rule while being practical in size.

Data must be collected over a range of vertical angles in 10° increments from 0° to 85°, and around a range of horizontal angles in 22.5° increments from 0° to 337.5°. If the photocell is aimed directly at the 4 x 4 ft. skylight from all angular positions, a room measuring 56 x 56 feet with a ceiling height of 28 ft. is needed. Location of such facility is difficult, and rental costs are likely to be high.

Two methods can be used to reduce the volume of a photometric test chamber while maintaining the 5x test distance:

1. Use of mirrors. Test paths can be folded within a reduced space by mirrors. For example, LSI's automotive goniometer test range provides a 100 ft. test distance but occupies only a 10 x 45 ft. space. It is a facility inspected, approved and used by the US Department of Transportation.

   The most common type of goniometer in use today is the rotating mirror system. LSI is the world's largest supplier of such systems and operates two such laboratories at the Arizona facilities.

   Use of mirrors in photometry therefore is accurate, when properly calibrated, and commonplace.

2. Testing of large light sources in multiple sections.

   A large source can be broken into individual sections, each of which is tested separately. This is achieved by using a screening plate, which fits over the luminaire to block light from the area not being measured. The area being measured is centered on the goniometer. LSI uses this technique for all 8 ft.

fluorescent luminaires, testing these in two 4 ft. sections and summing the results using software.

Both of the above techniques are used in this skylight photometry project, providing a high accuracy system for 4 ft. x 4 ft. skylights in a cube that measures 17 feet on each side.

The error inherent in this technique versus the error from standard far field photometry is described in Section 7 Error Analysis.

4.2. The Goniometer and Test Chamber

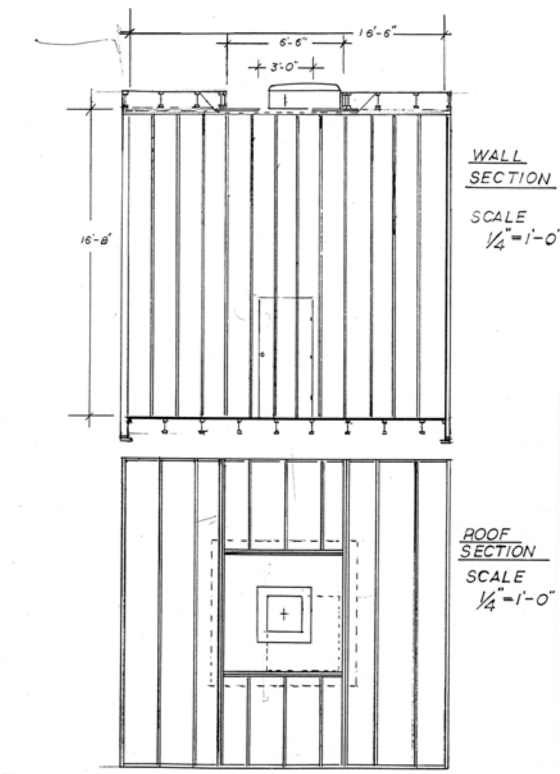


Figure 1: Photometric test chamber elevation and plan (reduced scale)

Lighting Sciences Inc (LSI) has built a hollow wooden cube that is approximately 17 ft on a side (see Figure). This cube has a 6.5 ft by 6.5 ft opening in the roof. The bottom of this opening (flush with the ceiling) is a steel plate which supports the skylight and the light well. In the center of this steel plate is a 2 ft by 2 ft hole - the size of a quadrant of a 4 ft by 4 ft skylight. This opening provides unrestricted light paths in the test chamber at all vertical angles to 85° for all azimuthal angles.

Each skylight is tested in four 2 x 2 ft. portions. The four photometric tests will be summed using software already available for this purpose. The goniometer system, as described below, is such as to allow each 2 x 2 ft. area to lie at the goniometer center while it is under test. Results therefore will be identical to those from a single test using double the test distance.

Figure 3 illustrates the goniometer. It is of the multiple photocell type, (see IES handbook), with an individual cell for each vertical angle of interest. (0, 5, 15, 25, 35, 45, 55, 65, 75 and 85 degrees.) The horizontal member holds the 0, 5 and 15 degree photocells. The 0 degree cell is directly beneath the exposed 2 x 2 ft. quadrant of the skylight under test. This horizontal arm pivots around an axis point directly beneath the 0° cell, with its opposite end running on a wheel. Full 360° horizontal rotation can be achieved.

Figure 2: Chamber opening and metal quadrant shield (prior to being lined with black paper)

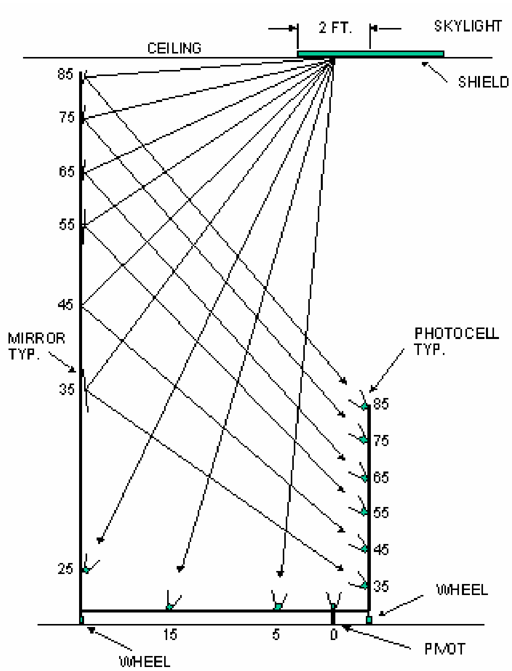


Figure 3: Side View of Goniometer

At the extremity of the horizontal arm is a vertical member, holding the 25° photocell. It also holds flat mirrors having centroids at vertical angles of 35, 45, 55, 65, 75 and 85° respectively. Each mirror is angled to redirect the intercepted light to individual photocells located on a second vertical arm. Each of the 35 to 85° cells "sees" the skylight at its particular angle and only at that angle.[1].

All mirrors and photocells, because they are mounted on the horizontal pivoting arm, rotate 360° about the 0° photocell to provide a complete photometric measurement system. A horizontal stabilizer arm with wheels and guide wires maintains the verticality of the arm holding the cells and mirrors as it rotates through the range of horizontal angles. A further wheel is placed beneath the second smaller vertical arm.

[1] One member of our advisory committee suggested measuring the skylights without the quadrant masking guard and comparing this to the results with the quadrant masking guard in place. The geometry of the mirrors and photometer baffles permits viewing only a 2 ft by 2 ft opening; thus, this suggestion could not be applied.

The skylight will be tested with one of its quadrants over the 2 x 2 ft. ceiling aperture. The skylight and well will then be moved to position quadrants 2, 3 and 4 respectively over the ceiling opening. Thus each quadrant can be tested.

Black flocked paper of very low reflectance (measured reflectance of 2%) will be placed on the plate underneath the well, over the 3 quadrants not being tested. This will reduce any unwanted reflections to near-zero.

4.3. Electronics

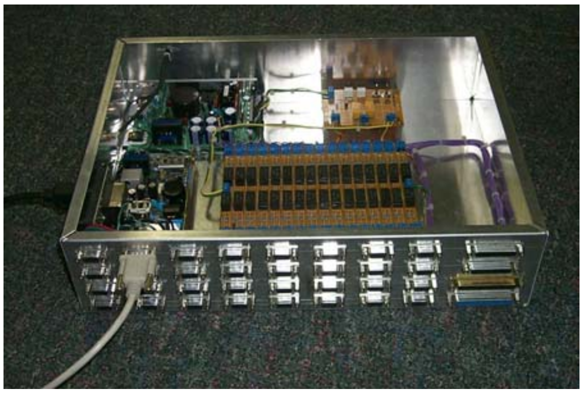


Figure 4: Multi-channel photocell signal amplifier

Each photocell is a silicon photodiode, with its spectral response corrected accurately to the CIE V(λ) curve. LSI has proprietary electronic systems which amplify the photocell signal using various amplifier gain stages appropriate for the light level under test. The amplified analog signal is converted to digital and sent to a computer interface. The entire system is multichannel such that the computer monitors all photocells simultaneously. Such electronics have been used on numerous other photometric test systems developed and produced by LSI. Accuracy of the proposed system will be equivalent to that of LSI's mirror goniophotometers.

4.4. Ambient solar illumination measurements

Figure 5: Ambient Light Meter and Obscuring Shield

A Photo Research model 301 illuminance meter/radiometer installed on the roof of the test chamber measured global horizontal illuminance. This same illuminance meter also measured horizontal diffuse illuminance when the sensor was shielded from the direct beam of sunlight. Shielding was accomplished by holding a 3.5 inch by 4 inch shield 18 inches from the photometer sensing element. The shield is attached to the end of an 18 inch long handle which allows the technicians to be approximately 2 feet away from the photometer. In addition, while holding the shield, the technicians stood on a roof that was approximately 4 feet lower than the test chamber, thus only the head and shoulders of the technicians were at the same level as the light sensor.

Both global horizontal and diffuse horizontal ambient illuminance measurements are taken at he beginning of each set of skylight measurements so the goniometric measurements of skylights are taken only under the correct sky conditions. Clear sky measurements for a given sun angle and skylight configuration will be taken only when the sky ratio (ratio of diffuse to total horizontal illuminance) is less than 25%. Overcast sky measurements will be taken only when the sky ratio is greater than 85%.

Ambient global horizontal illuminance measures are also taken simultaneously with each half vertical plane of intensities under the skylight for each increment in horizontal (azimuthal) angle. Thus each time the arm of the goniometer is moved, an ambient global horizontal illuminance measurement is taken. This is done so the candela measurements taken on the goniometer are normalized by the horizontal lumens falling on the skylight.

4.5. Solar Angles

LSI has provided a brief review of the computation of solar angles which will be needed in this project, see Appendix A - Solar Angle Calculations. Using the formulae provided, the exact test times will be computed for the actual day of testing for the 10° increments of the sun.

4.6. Data Collection Speed

It is important that data collection occurs at high speed as the results should not be affected significantly by movement of the sun during the test. The multiple cell photometer allows near-instantaneous capture of a vertical plane of readings. It is estimated that collection of such a plane and movement of the system to the next horizontal angle can be accomplished in 10 seconds. A full photometric test in 16 half-planes for a single skylight quadrant is completed in approximately 2 minutes, 40 seconds. Shielding of the skylight quadrant and exposure of the next quadrant is done by moving the skylight so that the next quadrant measured is over the square hole in the roof of the test chamber, taking roughly 20 seconds. A complete test on all four quadrants is estimated to require roughly 12 minutes.

A typical elapsed time for a 10° change in solar elevation is roughly 50 minutes. (See appendix A.) The solar elevation change during a 12 minute test will be roughly 2 degrees. By starting the test 6 minutes before the sun reaches the desired angle, test data will apply to this angle plus and minus approximately 1 degree.

4.7. Data Reduction

Conventional indoor lighting photometric data reduction software is unsuitable for the purpose of this project. Most software assumes that an indoor luminaire is quadrilaterally symmetric (symmetric about its along axis and about its across axis.) More general software will treat the data as symmetric only about the along axis, i.e. left and right sides symmetric. However, a skylight produces a light distribution that has no axis of symmetry. LSI will use software capable of handling all quadrants of the light distribution separately, and will write IES photometric files which properly document the data for each azimuthal plane, 0 to 360°, without any form of averaging.

The luminous intensities (cd) measured by the goniometer for each quadrant are normalized by the total amount of ambient luminous flux (lumen) falling on the entire skylight. Adding together the normalized luminous intensities (cd/lumen) from each of the four quadrant measurements generates the normalized luminous intensities for the photometric file for the entire skylight.

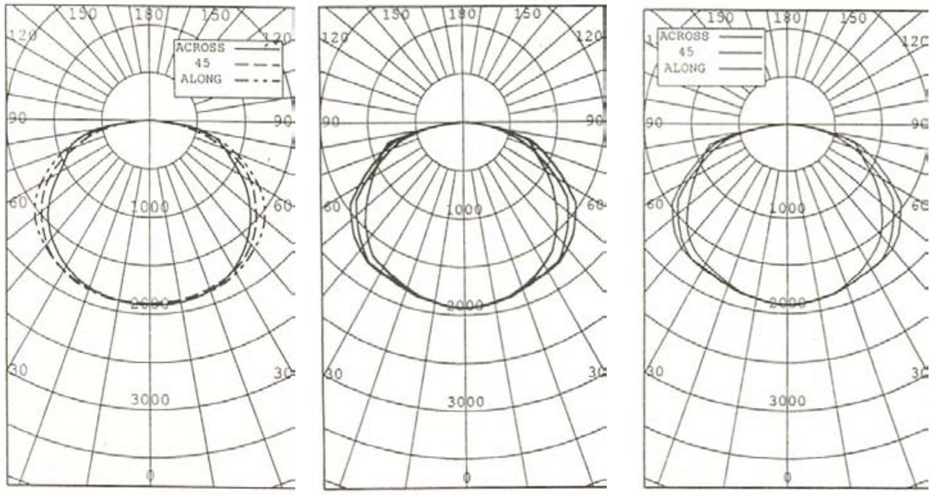
No adjustment is made for reflectance from shielding. The negligible error resulting from reflections off of the quadrant mask is quantified in Section 7 Error Analysis.

5. CALIBRATION

LSI operates a US Government approved calibrations facility for photometric devices, traceable to NIST.

The model 301 photometer for roof measurements is calibrated every 6 months using LSI's optical bench room and NIST traceable intensity standard lamps.

Calibration of a multiple cell goniometer such as that proposed is performed using a special form of standard lamp. This is a lamp and reflector combination which provides a wide spread of light. This source is calibrated over a range of vertical angles on a mirror goniophotometer, which is itself calibrated traceable to NIST. The standard source is then placed at the goniometer center, which in this case will be the center of the well at the height of the ceiling. Surrounding surfaces are black. Knowing the intensity in the direction of each photocell from the mirror goniophotometer calibration of this source, and reading the amplified voltage developed by each photocell, the candelas per millivolt factor for each cell is calculated. This array of calibration factors is stored in a computer file and applied to all subsequent millivolt readings during the actual testing. This yields the absolute candela values received by each cell during test.



a) standard photometer

b) skylight photometer pre-test

c) skylight photometer post-test

Figure 6: Comparison of 2 ft by 2ft luminaire measurements on standard goniometer (left) vs. skylight goniometer before and after clear sky skylight tests

The above calibration assures that the calibration is correct for a point source. Error could be created if the goniometer is slightly misaligned or baffles are shielding some of the area of the 2' x 2' planar source. To assure that all measurements are accurate for a planar source, measurements shall be taken of a 2' by 2' light fixture with a known asymmetric photometric distribution. These intensity measurements shall be compared with the known distribution and an error analysis performed.

As can be seen by viewing the polar plots in Figure 6 (a) and (b), the results from the skylight goniometer match well those from a standard mirror goniometer used to measure the photometrics of electric lighting luminaires. The total lumens calculated from intensities measured by the skylight goniometer were only 3% less than those of the standard goniometer. In terms of average intensities per vertical angle, only at 85 degrees from the nadir did the intensities diverge more than 10%. It is thought that the 1/2" thickness of the ceiling is blocking this last measurement at the glancing angle of 85 degrees. At this angle, representing the average intensity between 80 and 90 degrees, only 2% of total lumens from the luminaire were measured on the standard goniometer.

This comparison shows that the skylight goniometer is within acceptable criteria for accuracy to perform the tests.

In addition, the luminance distribution of the 2 ft by 2 ft electric lighting luminaire was measured on the skylight goniometer at the beginning and at the end of the clear sky tests. As shown in Figure 6 (b) and (c), there was little change in this measured luminance distribution of the same object between the beginning and the end of the tests. This indicates that sensitivities did not drift or that alignment of mirrors did not change over the period of the clear sky tests.

6. TEST PROTOCOL

The following steps describe the protocol used for photometric testing of the 22 skylight and light well combinations.

Step 1 Calibrate goniometer

Step 2 Install skylight

Step 3 Check for light leakage

Light should not be coming through base of skylight

Step 4 Check for appropriate sky ratio

The sky ratio is defined here as the ratio of diffuse horizontal illuminance to total horizontal illuminance.

Clear sky tests - less than 25% sky ratio

Overcast sky test - greater than 85% sky ratio

Diffuse horizontal illuminance is measured using an Illuminance meter with a shading disk.

Step 5 Start testing 6 minutes before solar elevation is at nominal 10 degree value

Step 6 Move skylight so correct quadrant is exposed

Schedule quadrant measurements so that the second and third quadrants tested (those closest to the nominal sun position) are the ones with the most light output for that time of day.

Step 7 Initial position of goniometer (North = 0 degrees)

This is compatible with some commercially available lighting software.

Step 8 Collect goniometer and ambient data

Goniometer candela measurements and ambient illuminance measurements taken simultaneously to create normalized candela per lumen values. Data collected on test rig with sensors located at mid point of each ten degrees of vertical angles and entire rig is rotated azimuthally in 22.5° increments the full 360°.

Step 9 Repeat steps 6 through 9 for remaining quadrants

Step 10 Repeat steps 4 through 10 for each 10 degrees of a full day's worth of data

Sky ratio must be valid for each test.

Check calibration of goniometer at end of tests to assure stability of measurements.

7. ERROR ANALYSIS

Sources of error, which will affect results, are those, which are normal to all (or most) photometric testing, and those, which are specific to this project. Normal sources of error are generally agreed to be within a range of ± 2% overall, although individual intensity values may vary by greater amounts. With certain difficult-to-measure light sources, this figure increases to roughly ± 5%.

Project-specific errors are as detailed below.

7.1. Sun Movement.

Measurement in 16 half-planes for each of the four skylight quadrants is estimated to take 3 minutes per quadrant for a total of 12 minutes. Testing will commence 6 minutes prior to the nominal time at which the sun reaches its test location. Thus data planes will be collected at times ranging from 0 to 6 minutes from the nominal condition. The error introduced by this factor in terms of skylight efficiency is expected to be negligible because of plus and minus canceling effects. Errors will be further reduced by measuring the two quadrants, which contribute the least to the overall light output before and after the two, which contribute the most. The errors introduced will affect intensity values at individual angles, but these also are not expected to be of practical significance.

7.2. Test distance

The IES rule-of-thumb is that photometric errors are negligible as long as the test distance is more than five times maximum dimension of the luminaire. By breaking a 4 X 4 foot skylight into 4 equal individual areas, the largest dimension of any test item will be less than one fifth of the test distance. This therefore does not introduce any error related to source size greater than that which occurs in conventional photometry. It is, in fact, equivalent to doubling the test distance.

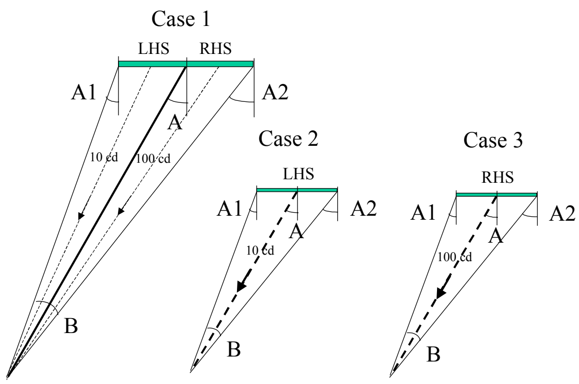


Figure 7: Geometric errors from subdivision of source

It has been queried what errors this technique may introduce if different portions of the skylight produce different levels of intensity in given directions. Case 1 in Figure 7 shows where a 4 x 4 ft. skylight is tested at 28 ft. This illustrates measurement at an angle A. The skylight subtends an angular range B, and the intercepted vertical angles range from A1 to A2. Consider left and right equal portions of the skylight, marked LHS and RHS. Suppose LHS projects an intensity of 10 cd towards the photocell, and that RHS projects 100 cd. Presume that the intensity from both sides decreases with increasing vertical angle.

The angular range projected from LHS to the photocell ranges from A to A1. This light is assigned to an angle A. All light from LHS is at angles lower than A and therefore this light will be recorded and assigned to angle A at too high an intensity.

Similar logic applies to RHS, excepting that its light assigned to angle A will be too low an intensity.

Because light emission from LHS is much less than from RHS, the overall error will result in too low an intensity being assigned to angle A.

Cases 2 and 3 in Figure 7 illustrate where the photometry is performed separately on the two sections at a test distance, which is half that used for case 1.

In case 2, the light assigned to A will actually be emitted over a range from A1 to A2. Providing the gradient of intensity change with angle is reasonably close to constant, the increased emission in the range A to A1 will be compensated by the decreased emission over the range A to A2. This will sharply reduce any errors.

In case 3, the same error cancellation occurs.

When the readings from cases 2 and 3 are summed, errors will be low because of the self-canceling tendency in the two individual cases. No such self-cancellation occurs in case 1. The summation method, case 2 + 3, is therefore inherently more accurate than case 1. Case 1 meets the requirements of LM41, therefore the case 2 + 3 method exceeds LM41 requirements

It is therefore logical to assume that errors introduced by spatial non-homogeneity of a 4 x 4 ft. skylight will be reduced by photometering in 2 x 2 ft. sections, rather than the errors being increased.

Where intensity gradients versus angle change sharply, the self-canceling in cases 2 and 3 will be imperfect, but, there will always be some self-cancellation of errors. In such cases, there is a possibility that errors will increase with cases 2 + 3 versus case 1 as the angular range of measurement for cases 2 and 3 is from A1 to A2, while that for case 1 is half that amount. Sharp changes in intensity gradient however, also are likely to introduce further errors in case 1.

Errors in the application of the skylight tests will exceed those from conventional luminaire tests to the degree that such non-homogenities are greater in the skylights. The extent of this effect is not known.

7.3. Reflectance Differences Between Mirrors.

Each photocell will be calibrated in situ, with the standard lamp located at the goniometric center of the skylight. Mirror reflectance differences, if any, will therefore be cancelled in the calibration process. Calibration accuracy of the standard lamp is $\pm$ 2%.

7.4. Atmospheric Changes During a Test.

The roof-mounted detectors will monitor any changes during a test and their readings will be used to factor the skylight data planes.

7.5. Error Checking.

As an overall check of system accuracy, LSI intends to perform testing of a 4 X 4 foot fluorescent luminaire on one of the laboratory's standard mirror photometers. This luminaire will then be located in the position of a skylight and photometered using the new equipment. The correlation will be studied. Any significant departures between the two data sets will be evaluated and eliminated.

7.6. Stray light reflected from quadrant masking shield

Since 3/4's of the base of the skylight well is covered by a shield during all measurements, some of the light reflected by the shield will ultimately make it through the open quadrant and be measured. This reflected light is a source of error as it is an artifact of the shielding process. We measured the reflectance of the black flocked paper that will cover the shield and found its reflectance to be 2%.

As illustrated in the calculations in Appendix B - Error Due to reflections from quadrant masking shield, the additional light resulting from reflections from the masking shield is less than 1% of the light we are intending to measure. Given the other experimental uncertainties, it is not warranted to create a correction factor for the negligible amount of light reflected by the masking shield that is measured by the goniophotometer.

8. LOCATION AND SITE

Scottsdale, Arizona is located at latitude of 33.5°, corresponding to southern California between San Diego (32.5°) and Los Angeles (34.0°). Climatic conditions are excellent for the performance of this type of work as the majority of days meet the requirement for clear sky. Overcast days also occur with regularity.

The skylight will be higher than the adjacent building. All other buildings in the area are low enough such that any shadowing created will be 6 degrees or less above the horizontal. Light blockage therefore is expected to be negligible. Shadowing by a few trees in the area is also considered negligible.

APPENDIX A - SOLAR ANGLE CALCULATIONS

Calculation of elapsed solar mean time between different solar elevations

We wish to compute the elapsed solar mean time between two different elevations of the sun. This can be accomplished by computing the hour angles of the sun for the two different elevations and subtracting the two angles. The elapsed solar mean time will be the difference in hour angle. The hour angle of any celestial object is the angle between the prime meridian and the great circle that runs through the object and the celestial poles. Hour angle is normally expressed in terms of hours, minutes, and seconds. A full circle of 360° is converted to 24 hours so that 15° are equivalent to 1 hour.

The relationship between an object's declination, δ, the observer's latitude, ϕ, the object's zenith distance, z, and the objects hour angle, H, is given by:

$$\cos z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos H.$$

W.M. Smart, Textbook on Spherical Astronomy 6th ed., Cambridge University Press, 1979, p.35.

Solving the equation for hour angle H gives:

$$H = \mathrm{Cos}^{-1}((\cos z - \sin \phi \sin \delta)/(\cos \phi \cos \delta)).$$

The zenith distance, z, is related to the elevation, e, by:

$$z = 90° - e.$$

So the equation for hour angle in terms of elevation is:

$$H = \mathrm{Cos}^{-1}((\sin e - \sin \phi \sin \delta)/(\cos \phi \cos \delta)).$$

This equation is technically for an object with a fixed declination and right ascension. However the sun is constantly changing its position with respect to the background stars. The right ascension of the sun changes by about 4 minutes per day. The elapsed time computed would be too small by 4 minutes per 24 hours of elapsed time. However the time interval computed from the hour angle is in sidereal time which runs faster than solar mean time by 4 minutes a day. Thus the error caused by the sun's changing right ascension is corrected by the conversion from sidereal to mean solar time.

The sun is also constantly changing its declination. For the time period between 7 May and 5 August the sun's declination changes by a maximum of about .5° per day. This should result in a maximum error of about 10 seconds per hour of elapsed time.

Another approximation implied in this method is that the difference in hour angle will be identical to the elapsed mean sidereal time. Technically differences in hour angle are related to differences in apparent sidereal time. The apparent sidereal time differs from mean sidereal time by something called the equation of the equinoxes. However the magnitude of the equation of the equinoxes is about 1 second so it can be safely neglected. Also the calculations are not corrected for atmospheric refraction and observers elevation above sea level.

As an example let us calculate the elapsed solar mean time between solar elevations in 10° increments for latitude 33.5° N (Scottsdale, Arizona) on 7 May 2001. From the 2001 edition of the Astronomical Almanac, we interpolate the solar declination for 19h UT (Noon MST) and obtain a declination of +16.9°. The times calculated are as follows:

Table 2: Duration of Elevation Changes on May 7th

Solar elevation change	Elapsed time (minutes)
0 - 10	50.2
10 - 20	48.8
20 - 30	48.1
30 - 40	48.0
40 - 50	48.7
50 - 60	51.2
60 - 70	61.7

The maximum solar elevation, e_{max}, at solar noon can be easily found by the following relationship.

$$e_{max} = 90 - \phi + \delta$$

Thus the maximum solar elevation in Scottsdale on May 7th would be:

$$e_{max} = 90 - 33.5 + 16.9 = 73.4 \text{ degrees}$$

Computations such as illustrated above will be used to determine exact skylight test times.

APPENDIX B - ERROR DUE TO REFLECTIONS FROM QUADRANT MASKING SHIELD

Conditions:

- Material will be black flocked surface, reflectance = 2.2%, as measured by LSI.
- Pattern of reflected light is Lambertian.
- Consider average depth of skylight well = 3 ft.

Suppose 100 lumens reach the 4 x 4 ft. bottom of the well. Lumens intercepted by the shield, on average, = 75 lms., as 12 sq. ft. out of 16 sq. ft. are shielded.

By computing the intensity distribution from a given point on the shield, assuming a Lambertian diffuser, and the solid angle subtended by the skylight itself (top aperture), and the solid angle subtended by the skylight well surfaces, the proportion of reflected light from the point reflecting and then striking the well surfaces can be calculated. Computations indicated that for a typical point on the quadrant masking shield, 75% of the reflected light will strike the skylight well and 25% will strike the skylight itself from underneath.

Thus for the 75 lumens incident on the shield top surface, the lumens reflected and then intercepted by the well surfaces = 75 x 0.022 x .75 = 1.24 lumens.

For a ray striking the well surface, which has a diffuse reflectance of 85%, 50% will reflect upwards, 50% downwards.

Amount of light reflected downwards = 1.24 x 0.85 x 0.5 = 0.53 lumens.

Of this, one quarter is likely to be transmitted through the aperture. (4 sq. ft. open out of the 16 sq. ft. total)

Amount of light reflected through opening = 0.25 x 0.53 = 0.13 lm **Equation 1**

For the 100 lumens, lumens reflected from the shield and intercepted by the skylight itself = 75 x 0.022 x .25 = 0.41 lumens.

Amount of light reflected upwards from the skylight well surfaces (after reflection from the shield) = 0.53 lumens. (Identical to light reflected downwards). Assume worst case, that all of this hits skylight.

Therefore total light striking bottom of skylight itself after reflection from the shield top = 0.41 + 0.53 = 0.94 lumens.

The reflectance of a sample skylight has been measured to be 7%. However, assume a more diffuse skylight with a higher reflectance of 20%.

Amount of light reflected by skylight after reflecting from shield top = 0.94 x 0.20 = 0.19 lumens.

Proportion of this light reaching 4 x 4' bottom of skylight well = 0.25 (using same logic as 75/25% earlier).

Of this, one quarter will be transmitted through the 2ft x 2 ft. aperture.

Therefore, light reflected from shield top and also reflecting from skylight itself =
0.19 x 0.25 x 0.25 = 0.01 lumens. **Equation 2**

From Equations 1 and 2, total light transmitted through 2 x 2' aperture after reflecting from shield top = 0.13 + 0.01 = 0.14 lumens.

When data for the four quadrants are summed, this error will be increase by a factor of 4 to 0.56 lumens.

The approximate error introduced by reflection from the shield is therefore 0.56%, as the above calculations are for 100 lumens reaching the bottom of the 4 x 4 ' well.

The error introduced from light reflecting of the masking shield is less than the expected measurement error and no adjustment factor is needed to correct for the presence of the shield.

P500-03-082-A-27

Photometric Testing Lessons Learned (product 5.3.2x)

Not yet complete

Please check the website in December 2003 for this document

Final REPORT

Skylight Test Chamber Design Report: Skylight U-factor Tests

By

Jon McHugh
HESCHONG MAHONE GROUP

Sam Yuan
ETC Laboratories, Inc.

July 10, 2002

Submitted to:
New Buildings Institute
Integrated Energy Systems
Productivity & Building Science Program
Contract Number Deliverable #5.3.2a

On behalf of the
California Energy Commission
Public Interest Energy Research (PIER) Program
Contract Number 400-99-013

Test Chamber Design for Skylight U-factor Test

Draft Report for Task 5.3.2a

Skylight U-factor Test Chamber Design

July 10, 2002
HMG Project #0014b

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Preface

The HESCHONG MAHONE GROUP has produced this report as part of the Integrated Design of Commercial Building Ceiling Systems research element of the *Integrated Energy Systems - Productivity and Buildings Science* energy research program managed by the New Buildings Institute. Cathy Higgins is the Senior Program Director of this project for the New Buildings Institute.
The *Integrated Energy Systems - Productivity and Buildings Science* program is funded by the California Energy Commission under Public Interest Energy Research (PIER) contract No. 400-99-013. The PIER program is funded by California ratepayers through California's System Benefit Charges and is administered by the California Energy Commission (CEC). Donald J. Aumann is the CEC Programmatic Contact.

ETC Laboratories, Inc. is contracted to conduct the skylight U-factors testing.

Legal Notice

Foreword

Approximately 75% of new retail construction makes use of dropped ceiling systems (T-bar and acoustical tile). Acoustic ceiling/lighting design affects fire protection, seismic safety, lighting, daylighting, insulation, mechanical systems and acoustics. Electric lighting accounts for over one third of all commercial electricity consumption, and over one quarter of peak demand for commercial buildings and 11% of peak demand for all uses in California! At least 60% of ceiling area is directly below a roof and therefore, how well building components and energy consuming systems are integrated to configure the ceiling system is a serious issue that impacts the resultant building energy use.

The purpose of this research element is to develop a protocol for designing and specifying highly efficient ceilings that will incorporate effective placement of insulation, daylighting via toplighting and daylight-responsive electric lighting controls. This protocol will help to reduce uncertainty regarding code compliance and construction costs.

This research in this report has been designed to support of the Integrated Design of Commercial Building Ceiling Systems research element. This research project consists of three related components:

1. Effectiveness of lay-in insulation
2. Comprehensive skylight testing
3. Culminating in an integrated ceiling system protocol for quality lighting (including daylight) and energy savings.

This report describes how a U-factor test facility was constructed and calibrated for the purpose of characterizing the thermal conductance properties of skylights with and without their light wells.

1 INTRODUCTION

The purpose of this report is to inform the California Energy Commission program manager, the advisory committee and other interested parties of the skylight products and skylight/light well combinations that will be tested for thermal performance (U-factor) and the test chamber design used to perform these tests.

We provide the Test Specimen Matrix in Section 2 and the Test Chamber Design in Section 4. Between these two sections we have sandwiched the Test Methodology. This test methodology in Section 3 has been previously reviewed by the advisory committee but is included in this report to provide context for review of the Test Specimen Matrix and the Test Chamber Design.

Since much of this work draws upon earlier solar heat gain tests on the same set of skylights, the reader is directed to the PIER skylight solar heat gain test plan document. This document was circulated to the PIER skylight testing advisory committee earlier. The results from the solar heat gain testing study will be also circulated to the advisory group this summer and will also be posted at the New Buildings Institute website: http://www.newbuildings.org/pier.

2 TEST SPECIMEN MATRIX

This project had selected eight types of skylights to identify the impact of glazing geometry, materials and number of glazings on their solar heat gain and thermal transmissivity. These skylights in order of their specimen number are:

1. Double clear low-e glass skylight mounted horizontally (similar to the skylights tested at Lawrence Berkeley Laboratory).[1]
2. Double clear low-e glass skylight mounted on a collar that imparts a 20° tilt to the skylight (similar to the skylights tested at Lawrence Berkeley Laboratory)
3. Single glazed medium white acrylic dome skylight – a very common type of diffusing skylight.
4. Double glazed clear over white dome skylight – very common skylight used over conditioned spaces; the extra layer of glazing reduces the thermal transmittance of the skylight.
5. Double glazed prismatic acrylic skylight with glazing shaped into a compound parabolic shape. Two companies in California are using this compound parabolic (catenary arch) shape.
6. Pyramidal skylight with fiberglass insulating panel (trade names of Kalwall or Skywall) glazing sections. Since we were testing the highest transmittance panel, there is no fiberglass batt between the two outer layers of fiberglass sheet glazing. The fiberglass sheet glazing is not pigmented (called crystal).
7. Pyramidal skylight with clear polycarbonate twinwall glazing. The twinwall material provides greater thermal resistance than single glazings and has greater stiffness than most single glazed plastics for situations where flat glazings are desired.
8. Single glazed bronze acrylic pyramidal skylight.

The skylights and skylight/light well combinations, shown in Table 1, were selected for the following reasons:

- These same skylights and light well combinations were tested for their solar heat gain coefficients in a solar calorimeter as part of this project
- Similar configurations of glass skylights were tested by Lawrence Berkeley Laboratory (LBL) in earlier research – this would provide a bridge between these tests and the LBL tests for comparison purposes
- Vertical tests and horizontal tests of skylights are compared to validate the current NFRC practice of testing skylights vertically to model their horizontal performance.

[1] J.H. Klems. “Solar Heat Gain through a Skylight in a Light Well,” ASHRAE Transactions Vol 108 Pt. 1 (2002) pp. 512-524.

All the vertical tests are performed with the skylight attached to a small (nominal 2” by 4”) curb which is in turn directly attached to the calorimeter. Thus the vertical tests do not have a light well.

The horizontal tests have light wells of varying heights (1 ft, 3 ft and 6 ft). The sides of the light wells are either diffusely reflecting (white paint) or are specularly reflecting (reflective metal sheet). In tests 10, 11 and 20, a light diffuser, a clear continuous acrylic sheet with an embossed prismatic pattern, is placed at the bottom of the light well.

This matrix also lists the test conditions for each test. The test conditions are described in *Section 3.4.14 Test Conditions.*

Table 1: Matrix of Skylight Test Specimens and Tests

Skylight Test Matrix

Test No.	Material	Shape	Color	Glazing(s)	Tilt	Well Ht.	Well Surf.	Well Diffuser	Conditions	Specimen No.
1	Glass	Planar	Clear	Double Clear/Low-E	Horz.	3'	Diffuse	No	Summer	1
2	Glass	Planar	Clear	Double Clear/Low-E	Horz.	3'	Specular	No	Summer	1
3	Glass	Planar	Clear	Double Clear/Low-E	20 Deg.	3'	Diffuse	No	Summer	2
4	Acrylic	Dome	White	Single	Horz.	1'	Diffuse	No	Summer	3
5	Acrylic	Dome	White	Single	Horz.	3'	Diffuse	No	Summer	3
6	Acrylic	Dome	White	Single	Horz.	6'	Diffuse	No	Summer	3
7	Acrylic	Dome	White	Double	Horz.	1'	Diffuse	No	Summer	4
8	Acrylic	Dome	White	Single	Horz.	3'	Specular	No	Summer	3
9	Acrylic	Dome	White	Single	Horz.	6'	Specular	No	Summer	3
10	Acrylic	Dome	White	Single	Horz.	3'	Specular	Yes	Summer	3
11	Acrylic	Dome	White	Single	Horz.	6'	Specular	Yes	Summer	3
12	Acrylic	Compound Arch	Clear Pris.	Double	Horz.	1'	Diffuse	No	Summer	5
13	Fiberglass	Pyramid	High White	Double Panel	Horz.	1'	Diffuse	No	Summer	6
14	Twinwall Poly.	Pyramid	Clear	Twinwall	Horz.	1'	Diffuse	No	Summer	7
15	Acrylic	Pyramid	Bronze	Single	Horz.	3'	Diffuse	No	Summer	8
16	Acrylic	Pyramid	Bronze	Single	Horz.	3'	Diffuse	Yes	Summer	8
17	Acrylic	Dome	White	Single	Horz.	1'	Diffuse	No	Winter	3
18	Acrylic	Dome	White	Single	Horz.	6'	Diffuse	No	Winter	3
19	Acrylic	Dome	White	Single	Horz.	6'	Specular	Yes	Winter	3
20	Acrylic	Dome	White	Single	Vert.	0	-	-	Summer	3
21	Acrylic	Dome	White	Double	Vert.	0	-	-	Summer	4
22	Acrylic	Compound Arch	Clear Pris.	Double	Vert.	0	-	-	Summer	5
23	Twinwall Poly.	Pyramid	Clear	Twinwall	Vert.	0	-	-	Summer	7
24	Acrylic	Pyramid	Bronze	Single	Vert.	0	-	-	Summer	8
25	Acrylic	Dome	White	Single	Vert.	0	-	-	Winter	3
26	Acrylic	Dome	White	Double	Vert.	0	-	-	Winter	4

3 METHODOLOGY

3.1 Scope

This test method covers the laboratory measurement of heat transfer through a skylight product and a skylight well assembly system under controlled air temperature, air velocity, and thermal radiation conditions. This method is typically designed for commercial skylight products and systems installed horizontally or in an angle on the roof of commercial buildings that have a roof plenum above the ceiling.

This test method is used for research purposes only. It is prepared for the purpose of a heat transfer investigation in skylight products and skylight well assembly systems on a contract agreement between the HESCHONG MAHONE GROUP and ETC Laboratories, Inc.

3.2 Referenced Documents

3.2.1 ASTM Standards:

C 177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded Hot Plate Apparatus

C 236 Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box[2]

C 518 Test Method for Steady-State Thermal Heat Flux Measurements and Transmission Properties by Means of the Heat Flow Meter Apparatus

C 870 Test Practice for Conditioning of Thermal Insulating Materials

C 976 Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box

C 1045 Practice for Calculated Thermal Transmission Properties from Steady-State Heat Flux Measurements

C1114 Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus

C 1199 Standard Test Method for Measuring the Steady State Thermal Resistance of Fenestration Systems Using Hot Box Method

C 1363 Test Method for Thermal Performance of Building Assemblies by Means of a Hot Box Apparatus

E 283 Test Method for Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors

E 631 Terminology of Building Constructions

E 783 Test Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors

E 1423 Practice for Determining the Steady-State Thermal Transmittance of Fenestration Systems

3.2.2 ISO Standards*:*

ISO 8990 Thermal Insulation-Determination of Steady- State Thermal Transmission Properties-Calibrated and Guarded Hot Box

ISO/DIS 12567 Thermal Insulation-Determination of Thermal Resistance of Components-Hot Box Method for Windows and Doors

3.2.3 Other Standards:

NFRC 100-97 Procedure for Determining Fenestration Product Thermal U-factors

ASHRAE Fundamentals Handbook, 1997

3.3 Terminology

Refer to ASTM C 1199 and C 1363

3.4 Summary of Method

This test method is used to measure the thermal transmittance of skylight products and skylight well assembly systems at horizontal or angled orientation.

3.4.1 Significance and Use

This test method is used for research purposes of skylight products and skylights with light well assembly systems. The main difference between this test method and normal fenestration thermal transmittance measurement as per ASTM C 1363 and C 1199 is the direction of the heat transfer through the test specimen. For the purpose of simulating the actual skylight and skylight system in commercial buildings, the test specimen in this test procedure is installed in a horizontal and/or angled orientation in the test facility.

When this method is used for measuring skylight well assembly systems, specific manufacturer's instructions on light well installation shall be followed. The total effective thermal transmittance of the skylight system is different with different light well materials, insulation and installation techniques.

3.4.2 Apparatus

3.4.2.1 Introduction

The test apparatus design is similar to a Guarded/Calibrated Hot Box that is used to measure the thermal transmittance of fenestration products installed in vertical positions. When it is used for a skylight well assembly, the light well should be surrounded by a conditioned plenum of which the air temperature is controlled.

3.4.2.2 Apparatus Design

The major components of a vertical heat flow test chamber are (1) the metering chamber on the bottom (usually on the ground and beneath the test specimen), (2) the test specimen frame with or without plenum on top of the metering chamber, (3) the weather chamber on top of the specimen, and (4) the surrounding ambient space. These components must be designed and built as a system to provide the controlled test conditions (such as air temperatures, air velocity, and radiation conditions) for the test specimen. Depending on the test specimen, the apparatus design on the specimen frame may differ. Only one surround panel is used when a skylight product (without well) is tested. For a skylight well assembly system, two surround panels are used to install the skylight specimen and the skylight well. In between the surround panels (alternatively called the ceiling frame and roof deck), a controlled plenum is established.

The design of the apparatus without plenum is shown in Figure 1.

The design of the apparatus with plenum is shown in Figure 2. In between the metering chamber on bottom and weather chamber on top, there is the test specimen with a light well surrounded by a conditioned plenum.

Both designs require that the surrounding ambient be conditioned at metering chamber temperature.

3.4.2.3 Apparatus Size—

No one size for the apparatus is considered to be standard. For research purposes, a maximum 10-foot wide by 10-foot long by 13-foot high test apparatus is recommended for a typical 4-foot long by 4-foot wide skylight with a 6-foot high light well assembly system.

3.4.2.4 Construction Materials—

Materials used in the construction of the test facility require a high thermal resistance. Polystyrene or other foam materials can be used since they combine high thermal resistance, good mechanical properties and ease of fabrication. To increase the physical strength of the chambers, facing materials such as fiberglass or rigid plastic materials are recommended on the exterior surfaces.

3.4.3 Metering Chamber

The size of the metering chamber is dependent on the area of a representative test specimen. The interior height (see Figure 1 and Figure 2) of the chamber should not be greater than that required to accommodate its necessary equipment. The metering chamber shall provide the control and measurement of air temperatures and velocities. Electrical heaters, cooling coils, and an air circulation system may be used to provide steady-state conditions to the test specimen. The energy transfer through the specimen at steady-state conditions equals the electrical power to the heaters and blowers minus the cooling energy extraction, corrected for the energy passing through the chamber walls and flanking the specimen. Both wall energy flow and flanking energy flow are determined from calibration measurements. To minimize the chamber wall heat transfer, the temperature difference of the chamber air and surrounding ambient shall be controlled as close to zero as possible. A thermopile shall be implemented on the chamber walls to measure the accumulative wall temperature difference.

To ensure uniform radiant heat transfer exposure of the specimen, all surfaces that can exchange radiation with the specimen shall have a total hemispherical emittance greater than 0.8.

3.4.4 Weather Chamber

The purpose of the weather chamber is to provide forced convection air flow over the specimen surfaces and the control and measurement of the fixed conditions such as air temperatures, air velocities on the side (top) of the specimen opposite the metering chamber. Electrical heaters, blowers, refrigeration system, and an air circulation system may be used. The chamber walls also shall be highly insulated materials.

3.4.5 Control Plenum

A control plenum is needed only when measuring a skylight well assembly system. The plenum shall be located between the skylight support frame (roof frame) and the light well support frame (ceiling frame). It shall be made of highly insulating materials and controlled at the same temperatures as the metering chamber. The plenum space surrounded by plenum walls, ceiling frame, light well walls, and the roof frame shall be controlled at the same temperature as the metering chamber.

3.4.6 Skylight Well Construction

The light well is supported by the ceiling frame and shall be constructed in accordance with the manufacturer's instruction. Characteristic measurement of light well material thermal conductivity shall be conducted in accordance with ASTM 518 or C 177. The light well wall surfaces shall be implemented with a thermopile to measure the accumulative temperature difference across the walls.

3.4.7 Specimen Frame

A specimen frame shall provide support to the test specimen and necessary perimeter insulation. The thickness of the specimen frame shall not be less than that of the metering chamber wall. Highly insulated material shall be used for the frame. The frame materials shall also be measured in accordance with ASTM C 518 or C 177 to obtain their thermal conductivity values. A thermopile of surface temperatures shall be measured under steady-state conditions.

3.4.8 Ceiling Frame

Ceiling frame is used to support the light well and form the light well control plenum. The requirements for specimen frames apply to the ceiling frame.

3.4.9 Air Circulation

An air circulation system shall be established in accordance with ASTM C 1363. The uniformity of air curtain velocity should be verified. The actual air velocity during the thermal testing shall be recorded.

3.4.10 Air Temperature Control

Air entering the air curtain shall be uniform in temperature across its width and it shall not change more than ±0.5°F during the steady-state measurement period. Both heating and cooling in both metering and weather chambers should be installed to provide winter and/or summer test conditions. The air temperature in the light well plenum shall be controlled at room conditions. More detailed methods on temperature control can be found in ASTM C 1363.

3.4.11 Temperature Measurement

All air and surface temperature measurements shall be made in accordance with ASTM C 1363. If measuring a skylight well system, light well air temperature shall be measured at different elevations. Also the light well wall surface temperatures or temperature difference shall be measured. The number of air and surface thermocouples shall be within ±10% of N calculated using the following equation:

$$N = \frac{0.9A}{0.07 + 0.08\sqrt{A}} \tag{1}$$

where

N: the number of thermocouples required;

A: temperature measurement area.

3.4.12 Instruments

All instruments used in the test facility shall conform with the requirements outlined in ASTM C 1363.

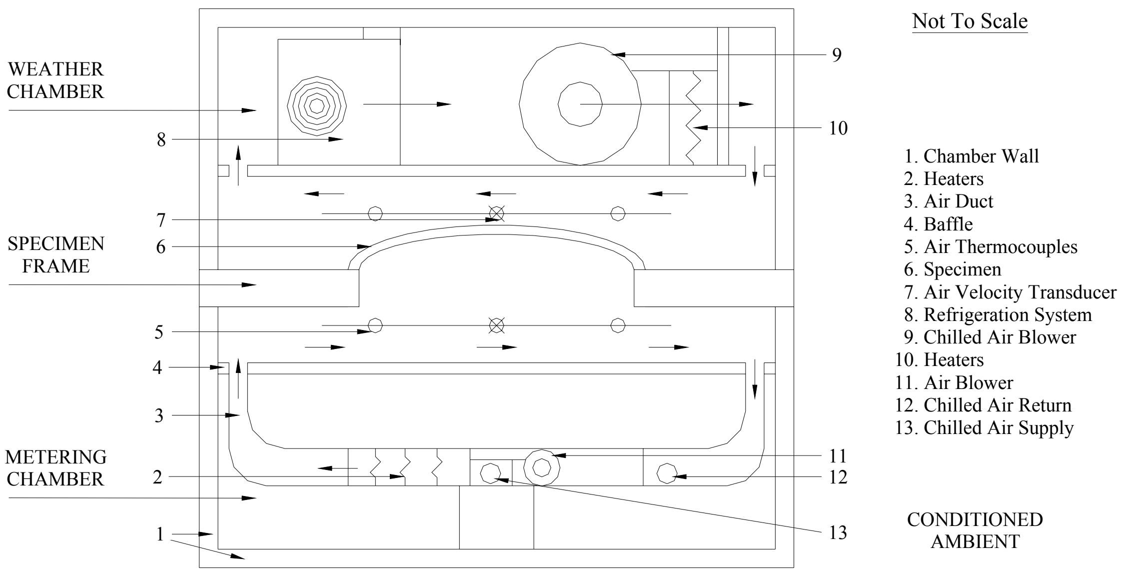

Figure 1 : Vertical Heat Flow Test Facility for Skylight Products

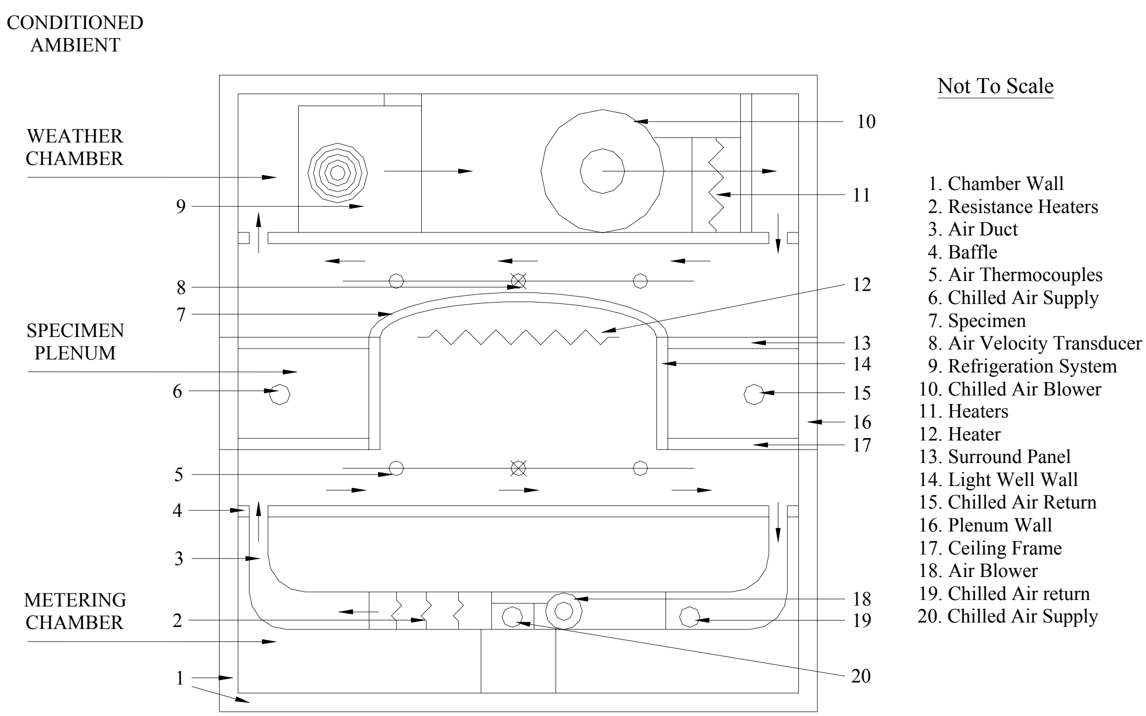

Figure 2 : Vertical Heat Flow Test Facility for Skylight with Light Well Systems

3.4.13 Test Specimen

Test specimen shall be representative of typical commercial applications. The modification of specimen construction before and during specimen installation shall be avoided.

The specimen size, mounting methods, thermocoupling and sealing shall follow the requirements of ASTM C 1363.

3.4.14 Test Conditions

3.4.14.1 Winter and Summer Conditions for Horizontal Orientation

According to ASHRAE (American Society for Heating, Refrigerating and Air-conditioning Engineers) winter and summer design conditions, the wind speed on the weather side for winter and summer conditions are 15 mph (miles per hour) and 7.5 mph, respectively. The velocity of both the metering room air and the light well inside air should be maintained below 0.67 mph (0.3 m/s) to obtain natural convection. The following tables show the standardized surface heat transfer coefficients for different skylight configurations and conditions. T_w is the temperature of the light well inside air. The tolerance for actual CTS surface heat transfer coefficients during calibration would be ±5% on the metering (and/or light well) side, ±10% on the weather side.

Table 2 : Test conditions for skylight only in horizontal orientation

Test Conditions	Metering Side		Weather Side	
	T_h (°F)	$h_{h,st}$ (Btu/h·ft^2·F)	T_c (°F)	$h_{c,st}$ (Btu/h·ft^2·F)
Winter	70	1.63	0	5.66
Summer	75	1.08	95	2.11

Table 3 : Test conditions for skylight with light well system in horizontal orientation

Test Conditions	Metering / Light Well Side			Weather Side	
	T_h (°F)	T_w (°F)	$h_{h,st}$ (Btu/h·ft^2·F)	T_c (°F)	$h_{c,st}$ (Btu/h·ft^2·F)
Winter	70	85	1.71	0	5.67
Summer	75	125	1.67	95	2.15

3.4.14.2 Criteria of Stead-State Test Conditions

Determining steady-state involves two separate evaluations. First, a series of four one-hour sets of data are compared to the group mean to determine if steady state has been achieved. Second, two additional consecutive two-hour test periods are individually compared to the average initial four-hour period and each other to verify steady-state conditions are maintained. The following tests are applied to both assessments.

The average room and weather side air temperatures and all other surface temperatures shall not vary by more than ± 0.25°C (± 0.5°F) over the entire eight (8) hour steady state period. (see ASTM 1363 requirements), nor vary in the same direction for any two consecutive periods.

The total heat flow into or out of the metering box, Q (including $Q_{mb,}$ Q_{fl}, and warm room heater and circulating fan power) shall be used to determine steady state. The mean of the four one-hour steady state periods shall agree within ± 1% of the mean of each of the two-hour test periods and each of the two (2) two-hour test periods must be within ± 1% of one another.

3.4.15 Calibrations

3.4.15.1 Metering Chamber Extraneous Heat Transfer:

Metering chamber extraneous heat transfer combines metering chamber wall heat transfer and surround panel flanking heat transfer. Full surround panel shall be used in this calibration. The calibration shall be conducted at the conditions shown in Table 4. Nine calibration experiments shall be conducted.

Table 4 : Standard conditions for the calibration of extraneous heat transfer Q_{EXTR}

Condition	Unit	Setting		
V_h	m/s (mph)	≤ 0.3 (0.67)		
V_c	m/s (mph)	6.67 (15)		
h_{STh}	W/(m^2·K) [Btu/(h·ft^2·°F)]	7.7 (1.35)		
h_{STc}	W/(m^2·K) [Btu/(h·ft^2·°F)]	29.0 (5.10)		
t_h	°C (°F)	21.1 (70.0)		
$t_{Amb.}$	°C (°F)	19.4 (67.0)	21.1 (70.0)	22.8 (73.0)
t_c	°C (°F)	-20.6 (-5.0)	-20.6 (-5.0)	-20.6 (-5.0)
		-17.8 (0.0)	-17.8 (0.0)	-17.8 (0.0)
		-15.0 (5.0)	-15.0 (5.0)	-15.0 (5.0)

3.4.15.2 Planar Calibration Transfer Standard

A planar Calibration Transfer Standard (CTS) should be used to calibrate the specimen surface heat transfer coefficients and the fan or blower settings on both metering and weather side. The construction and calibration procedure shall follow ASTM C 1199 Section 5.

3.4.15.3 Non-planar Calibration Transfer Standard

A five sided CTS should be constructed for measuring curved, pyramid, dome or other shaped skylight products. Each side shall be a planar CTS and four sided CTS should be attached to the top CTS with each side at 135° to the top CTS surface. The calibration procedure is the same as that for the planar CTS.

3.4.15.4 CTS without Skylight Well

For the CTS calibration without skylight well, only surround panel is used to support the CTS. There is no light well plenum.

3.4.15.5 CTS with Skylight Well

The plenum should be controlled at the same conditions as the metering chamber. Only natural convection is allowed inside the plenum. The light well should be sealed together with the CTS to minimize any air leakage through any interface.

3.4.16 Conditioning

10.1. Pre-test conditioning on the test specimen shall be in ambient air at 75°F with 50% relative humidity. For details, see ASTM Practice C 870 for guidance.

3.5 Test Procedure

3.5.1 Installation of Test Specimen:

The fenestration system to be tested should be installed in the surround panel with a configuration that simulates the actual (manufacturer's recommended) installation as closely as possible. That is, the complete assembly including all frame elements should be in place during the test. The surround panel requirements specified in ASTM C 1199 Section 5.1.2 and the sealing requirements specified in ASTM C 1199 Section 5.1.5 (for the calibration transfer standard) also apply to the test specimen. See 7.1 of Practice E 1423 for further guidance on installation.

3.5.2 Stabilization and Test Times:

Establish, as per Section 10.9 of Test Method C 1363 and Section 3.4.14 above, steady-state temperature and power conditions for which the test specimen is to be tested and record measurements of power, temperatures, and velocity at the specified test intervals.

3.5.3 Recorded Test Measurements:

3.5.3.1 Power Measurements

The energy balance to determine the total net heat transfer or average power transferred through the test specimen during a measurement interval should account for all metering box heating and cooling, power to fans or blowers, any significant power to transducers, corrections for the metering box wall heat transfer and surround panel and test frame flanking heat transfer, any other extraneous heat flows, and corrections for the energy flow (enthalpy difference times air leakage mass flow rate) associated with any air leakage entering and leaving the metering chamber.

3.5.3.2 Temperature Measurements

a. Perform all measurements specified in Test Methods C 236, C 976, or C 1363. The temperature sensors used should be special limit (premium) thermocouples (24 gage may be used; 30 gage or smaller are recommended for the test specimen surface temperatures), or appropriate size thermistors or RTD's (resistance temperature detectors).
b. Additional temperature measurements shall be made on the surround panel wall (see Section 6.5.2 of ASTM C 236, Section 5.7 of ASTM C 976, or Section 6.10.2 of ASTM C 1363).

c. Specimen surface temperatures shall also be measured in accordance with ASTM C 1199. It must be recognized that there is such a wide range of fenestration system designs that it is not possible to specify the locations of the temperature sensors to provide a correct area weighted determination of the various surface temperatures for all configurations. See Practice E 1423 for additional guidance on the location of test specimen surface temperature sensors for different fenestration systems. The temperature sensors used should be special limit (premium) thermocouples 24 gage (0.02010 in., 0.5106 mm), 30 gage (0.01003 in., 0.2546 mm) or smaller are recommended for the surface temperatures), thermistors or resistance temperature detectors (RTD's), and shall be placed so as to minimize the disturbance of the air flows on the surfaces of the test specimen. For the complex skylight specimens (such as domed, pyramid-shaped skylights), surface thermocouple locations should represent all different edges, corners, joints and so forth. Computer simulation results of temperature distributions obtained by Therm calculations may be used as a reference.

d. Temperature measurements should also be made in the room side and weather side air streams in the same quantity and spacing as the surface temperature sensors (see Section 6.5.2 of Test Method C 236, Section 5.7 of Test Method C 976, and Section 6.10.3.1 of Test Method C 1363). This will allow for a more accurate measurement of the room side and weather side surface heat transfer coefficients.

3.5.3.3 Radiation Effects

To minimize the effect of radiation-induced error on the temperature sensors, the temperatures of all surfaces exchanging radiation heat transfer with the fenestration system (test specimen or calibration transfer standard) shall be measured. This includes: (1) metering side and weather side shields and baffles, (2) air distribution system components, and (3) chamber walls and portions of the surround panel that are in view of the test specimen. Any heating and cooling devices must be shielded from the surround panel/fenestration system and the surface temperature of the shield should be measured. The temperature sensors must be applied to these surfaces with tape or adhesive that has an emissivity similar to that of the surface. The air temperature sensors should either be shielded or be as small as possible so that they are not significantly affected by surfaces with which they are exchanging radiation (see Section 6.5.2 of Test Method C 236, Section 5.7 of Test Method C 976, or Section 6.10.3.1 of Test Method C 1363).

3.5.3.4 Wind Speed Measurements

The weather side wind speed shall be measured at a location that represents the free stream condition. For both perpendicular and parallel flow patterns, it is required that this location be a distance out in the air stream such that the wind speed sensor is not in the test specimen surface boundary layers region. A minimum distance of 75 mm (3 in.) out from the test specimen center point is recommended. The hot box operator's experience and knowledge of the air distribution system and hot box design should be drawn upon to determine the proper location.

Mapping the velocity fields on both the room and weather sides, by periodic traversing of the air-flow field to determine the air velocity distribution, is recommended. This should be done at every calibration interval to verify that a uniform air flow is directed at or across the face of the test specimen.

On the room side, where natural convection conditions are desired, it is required to mount a velocity sensor at a location that represents the average velocity so that natural convection conditions can be verified and the room side average air velocity can be measured during the test.

3.5.3.5 Glazing Deflection

Glazing deflection measurements shall be reported for each skylight test specimen as specified in Practice E 1423.

3.6 Calculation

3.6.1 Summer Conditions for Skylight Test Specimen Only

Figure 3 shows the schematic of heat flows under summer conditions in the test setup of skylight specimen only.

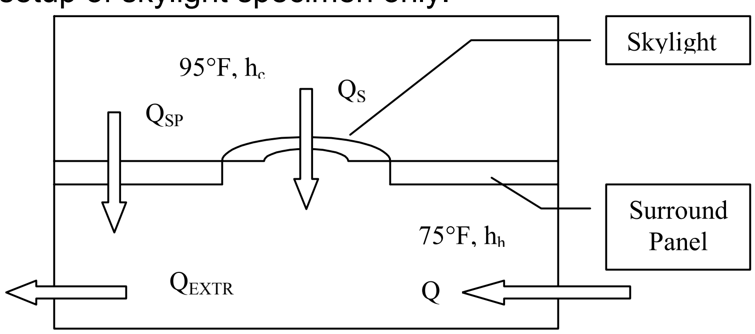

Figure 3 : Schematic Heat Flow in the Test Apparatus for Skylight Only Under Summer Conditions

The following shall be calculated for each test of skylight specimen without a skylight well:

3.6.1.1 Heat Extraction, Q

The time rate of heat flow out of the metering chamber.

3.6.1.2 Surround Panel Heat Flow, Q_{SP},

$$Q_{SP} = C_{SP} \cdot A_{SP} \cdot (t_{SP2} - t_{SP1}) \quad (2)$$

where:

C_{SP}: thermal conductance of the surround panel measured using Test Methods C 177, C 518, or C 1114 (W/m^2·K),

A_{SP}: projected area of the surround panel (m^2),

t_{SP1}: average of metering side surround panel surface temperature (°C),

t_{SP2}: average of weather side surround panel surface temperature (°C).

3.6.1.3 Metering Chamber Extraneous Heat Flow Q_{EXTR}

The extraneous heat transfer that does not flow directly though the test specimen and the surround panel, as determined using the procedure specified in Section 3.4.15.1.

3.6.1.4 Test Specimen Heat Flow, Qs,

$$Q_S = Q - Q_{SP} - Q_{EXTR} \quad (3)$$

3.6.1.5 Test Specimen Thermal Transmittance, U_S,

$$U_S = Q_S / [A_S \cdot (t_c - t_h)] \quad (4)$$

where:

A_S: projected area of the test specimen (m^2),

t_h: average of metering chamber air temperature (°C),

t_c: average of weather chamber air temperature (°C).

3.6.2 Winter Conditions for Skylight Test Specimen Only

Figure 4 shows the schematic of heat flows under winter conditions in the test setup of skylight specimen only.

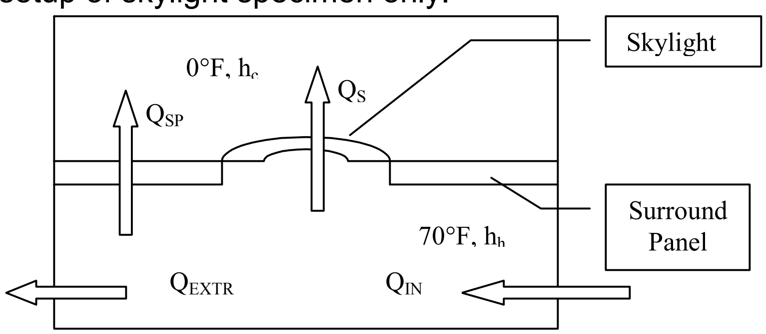

Figure 4 : Schematic Heat Flow in the Test Apparatus

The following shall be calculated for each test of skylight specimen without a skylight well:

3.6.2.1 Total Heat Input, Q_{IN}

The time rate of heat flow into the metering chamber.

3.6.2.2 Surround Panel Heat Flow, Q_{SP},

$$Q_{SP} = C_{SP} \cdot A_{SP} \cdot (t_{SP1} - t_{SP2}) \quad (5)$$

where:

C_{SP}: thermal conductance of the surround panel measured using Test Methods C 177, C 518, or C 1114 ($W/m^2 \cdot K$),

A_{SP}: projected area of the surround panel (m^2),

t_{SP1}: average of metering side surround panel surface temperature (°C),

t_{SP2}: average of weather side surround panel surface temperature (°C).

3.6.2.3 Metering Chamber Extraneous Heat Flow Q_{EXTR}

The extraneous heat transfer that does not flow directly though the test specimen and the surround panel, as determined using the procedure specified in Section 3.4.15.1.

3.6.2.4 Test Specimen Heat Flow, Qs,

$$Q_S = Q_{IN} - Q_{SP} - Q_{EXTR} \quad (6)$$

3.6.2.5 Test Specimen Thermal Transmittance, U_S,

$$U_S = Q_S / [A_S \cdot (t_h - t_c)] \quad (7)$$

where:

A_S: projected area of the test specimen (m^2),

t_h: average of metering chamber air temperature (°C),

t_c: average of weather chamber air temperature (°C).

3.6.3 Summer Conditions for Skylight Well Assembly System

Figure 5 shows the schematic of heat flows under summer conditions in the test setup of skylight well assembly.

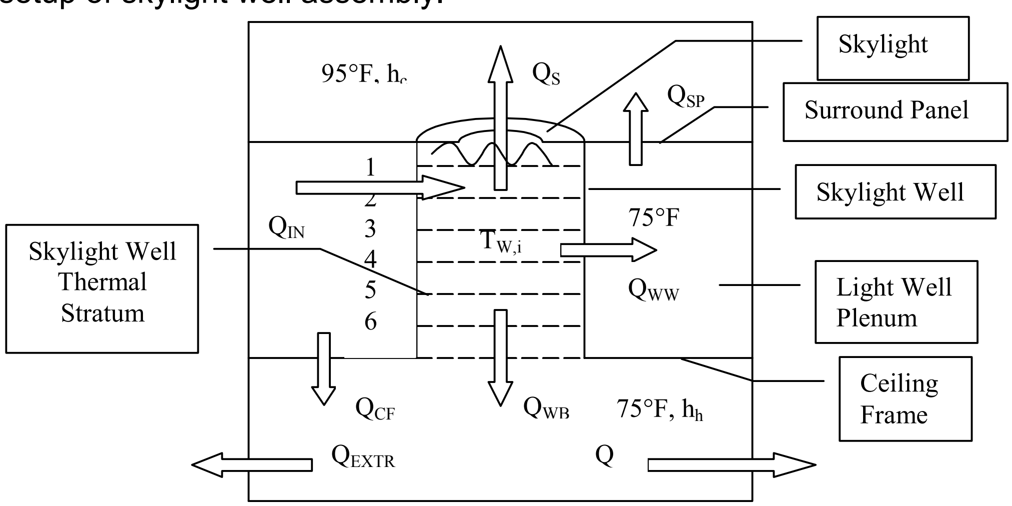

Figure 5 : Schematic Heat Flow in the Test Apparatus for Skylights Well Systems Under Summer Conditions

The following shall be calculated for each test of skylight well system:

3.6.3.1 Extraction Heat Flow, Q

The time rate of heat extracted from the metering chamber.

3.6.3.2 Ceiling Frame Heat Flow, Q_{CF},

$$Q_{CF} = C_{CF} \cdot A_{CF} \cdot (t_{CF2} - t_{CF1}) \quad (8)$$

where:

C_{CF}: thermal conductance of the ceiling frame measured using Test Methods C 177, C 518, or C 1114 ($W/m^2 \cdot K$),

A_{CF}: projected area of the ceiling frame (m^2),

t_{CF1}: average of metering side ceiling frame surface temperature (°C),

t_{CF2}: average of plenum side ceiling frame surface temperature (°C).

3.6.3.3 Metering Chamber Extraneous Heat Flow Q_{EXTR}

The extraneous heat transfer that does not flow directly though the test specimen and the surround panel, as determined using the procedure specified in Section 3.4.15.1.

3.6.3.4 Skylight Well Bottom Heat Flow, Q_{WB}

Heat flow through the skylight well bottom diffuser or the imaginary horizontal surface that closes the skylight well if there is no diffuser at the well bottom. It is calculated as:

$$Q_{WB} = (Q - Q_{CF}) + Q_{EXTR} \quad (9)$$

3.6.3.5 Surround Panel Heat Flow, Q_{SP}

Calculated using Equation (5) in Section 3.6.1.2.

3.6.3.6 Skylight Well Top Heat Flow, Q_{IN}

The time rate of heat input into the heater on top of the skylight well.

3.6.3.7 Skylight Well Heat Flow, Q_{WW}

The heat flow through the skylight well side walls. It is calculated as:

$$Q_{WW} = C_{WW} \cdot A_{WW} \cdot (t_{WWi} - t_{WWe}) \quad (10)$$

where:

C_{WW}: thermal conductance of the skylight well walls measured using Test Methods C 177, C 518, or C 1114 ($W/m^2 \cdot K$),

A_{WW}: total projected area of the skylight well walls (m^2),

t_{WWi}: average of interior well wall surface temperature (°C),

t_{WWe}: average of exterior well wall surface (facing the plenum) temperature (°C).

3.6.3.8 Test Specimen Heat Flow, Qs,

$$Q_S = Q_{IN} - Q_{SP} - Q_{WW} - Q_{WB} \quad (11)$$

3.6.3.9 Test Specimen Thermal Transmittance, U_S,

$$U_S = Q_S / [A_S \cdot (t_c - t_W)] \quad (12)$$

where:

A_S: projected area of the test specimen (m^2),

t_W: average of the top interior light well air temperature (°C),

t_c: average of weather chamber air temperature (°C).

3.6.4 Winter Conditions for Skylight Well Assembly System

Figure 6 shows the schematic of heat flows under winter conditions in the test setup of skylight well assembly.

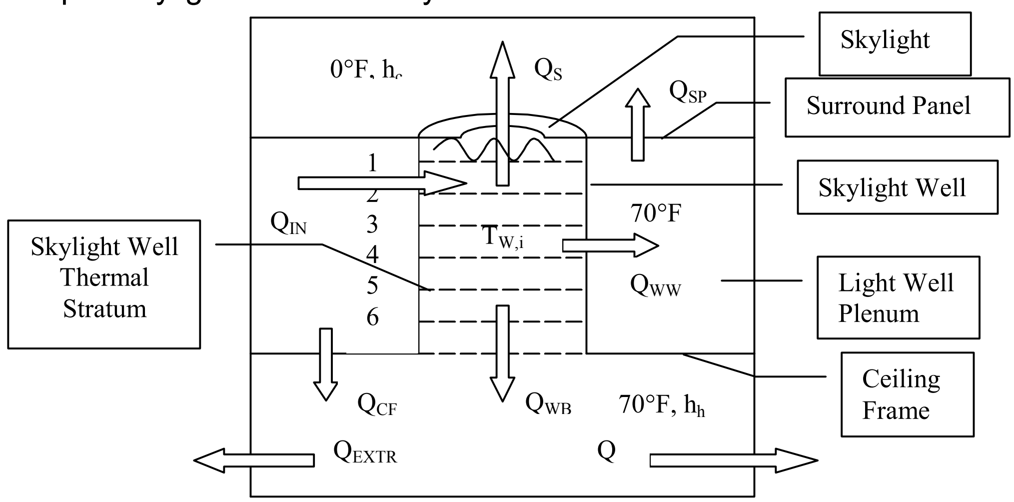

Figure 6: Schematic Heat Flow in the Test Apparatus for Skylight Well Systems Under Winter Conditions

The following shall be calculated for each test of skylight well system:

3.6.4.1 Extraction Heat Flow, Q

The time rate of heat extracted from the metering chamber.

3.6.4.2 Ceiling Frame Heat Flow, Q_{CF}

Calculated using Equation (8) in Section 3.6.3.2.

3.6.4.3 Metering Chamber Extraneous Heat Flow Q_{EXTR}

The extraneous heat transfer that does not flow directly though the test specimen and the surround panel, as determined using the procedure specified in Section 3.4.15.1.

3.6.4.4 Skylight Well Bottom Heat Flow, Q_{WB}

Calculated using Equation (9) in Section 3.6.3.4.

3.6.4.5 Surround Panel Heat Flow, Q_{SP}

Calculated using Equation (5) in Section 3.6.2.2.

3.6.4.6 Skylight Well Top Heat Flow, Q_{IN}

The time rate of heat input into the heater on top of the skylight well.

3.6.4.7 Skylight Well Heat Flow, Q_{WW}

Calculated using Equation (10) in Section 3.6.3.7.

3.6.4.8 Test Specimen Heat Flow, Qs

Calculated using Equation (11) in Section 3.6.3.8.

3.6.4.9 Test Specimen Thermal Transmittance, U_S

Calculated using Equation (12) in Section 3.6.3.9.

3.7 Test Report

The test report will provide all of the information specified in Test Method C 1363, Section 12. The test specimen size, design drawing(s), and a detailed description of all the test specimen components (that is, frame, glazing, hardware weather-stripping, etc.) also shall be reported. Any nonstandard test specimen size and non- standard test conditions used shall be explained. The following values will be reported:

3.7.1. The time rate of heat flow through the total surround panel/test specimen, Q.

3.7.2. The surround panel calculated time rate of heat flow, Q_{SP}.

3.7.3. The time rate of metering chamber extraneous heat flow for the surround panel, Q_{EXTR}.

3.7.4. The net test specimen heat flow rate, Q_S.

3.7.5. The heat flow through the skylight well wall if a skylight well system is measured, Q_{WW}.

3.7.6. The heat flow through the ceiling frame if a skylight well system is measured, Q_{CF}.

3.7.7. The heat flow through the skylight well bottom diffuser or the imaginary bottom horizontal surface if a skylight well system is measured, QWB.

3.7.8. The power input into the heater in the top of the skylight well inside space if a skylight well system is measured, Q_{IN}.

3.7.9. The test specimen room side and weather side heat transfer surface areas, A_h and A_c.

3.7.10. The average ambient air temperature, tAMB.

3.7.11. The plenum average air temperature if a skylight well system is measured, tp.

3.7.12. The skylight well interior air temperatures at different elevations if a skylight well system is measured, tW,i, where i is 1,2, ..., M (M is the total number of rows of well wall surface thermocouples).

3.7.13. The well air thermocouples should be located at the same rows as well wall surface thermocouples. The air thermocouple junctions should be perpendicular to the wall and 3-inch away from the wall surface toward the center of the well space.

3.7.14. The weather side and room side average baffle temperatures, tb1, and tb2.

3.7.15. The weather side and plenum side average surround panel surface temperatures, tSP1, and tSP2.

3.7.16. The skylight well side and plenum side average well wall surface temperatures if a skylight well system is measured, tWWi, and tWWe.

3.7.17. The metering room side and plenum side average ceiling frame surface temperatures if a skylight well system is measured, tCF1, and tCF2.

3.7.18. The surround panel projected area, ASP.

3.7.19. The ceiling frame projected area if a skylight well system is measured, ACF.

3.7.20. The skylight well wall projected area if a skylight well system is measured, AWW.

3.7.21. The room side and weather side baffle areas, Ab1 and Ab2.

3.7.22. The measured thermal transmittance of the test specimen, U_S.

3.7.1.1 Keywords

- vertical heat transfer,
- skylight,
- skylight well,
- thermal transmittance,
- U-factor,
- steady-state,
- testing,
- measurement,
- chamber,
- plenum,
- fenestration.

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(5) Incropera, F.P., and DeWitt, D.P. 1996. *Fundamentals of Heat Transfer*. Fourth Edition, John Wiley & Sons, Inc., New York.

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4 SKYLIGHT TEST CHAMBER DESIGN

This section provides a detailed description of the test chamber, and is in accordance with the general requirements of test article design outlined in the test method, "*Test Method for Measuring Thermal Properties of Commercial Skylight Products and Skylight Well Assembly Systems Using a Vertical Heat Flow Test Facility*". Based on the test matrix, only the new test apparatus used for measuring commercial skylight with well systems in horizontal positions is required in this research project. Therefore, the design for the horizontal test apparatus is presented in this document. Since there are three different heights of skylight well required, the test article has three different designs of details.

4.1 General Design

The major components of the test article are (1) the metering chamber on the bottom (supported by a 6-inch wood flame on the ground and beneath the test specimen), (2) the test specimen and skylight well with plenum assembly on top of the metering chamber, (3) the weather chamber on top of the specimen, and (4) the surrounding ambient space. Depending on the test specimen and skylight well height, the apparatus design is different on middle assembly (2). The general design of the apparatus with plenum is shown in Figure 1. In between the metering chamber on bottom and weather chamber on top, there is the test specimen with a skylight well surrounded by a conditioned plenum.

4.1.1 Apparatus Size

The test apparatus is 10-foot wide by 10-foot. Depending on different types of test specimen and skylight well height, there are different overall heights of the apparatus as described in section 3.

4.1.2 Construction Materials

Materials used in the construction of the test facility are Extruded Polystyrene (EPS) or other foam materials have been used since they combine high thermal resistance, good mechanical properties and ease of fabrication. To increase the physical strength of the chambers, facing materials such as fiberglass, plywood, or rigid plastic materials will be used.

4.1.3 Metering Chamber

The size of the metering chamber is approximately 10-foot by 10-foot by 3-foot. The metering chamber provides the control and measurement of air temperatures and velocities. Electrical heaters, cooling coils, and an air circulation system is used to provide stead-state conditions to the test specimen. Both wall energy flow and flanking energy flow are determined from calibration measurements. A thermopile is used on the chamber walls to measure the accumulative wall temperature difference.

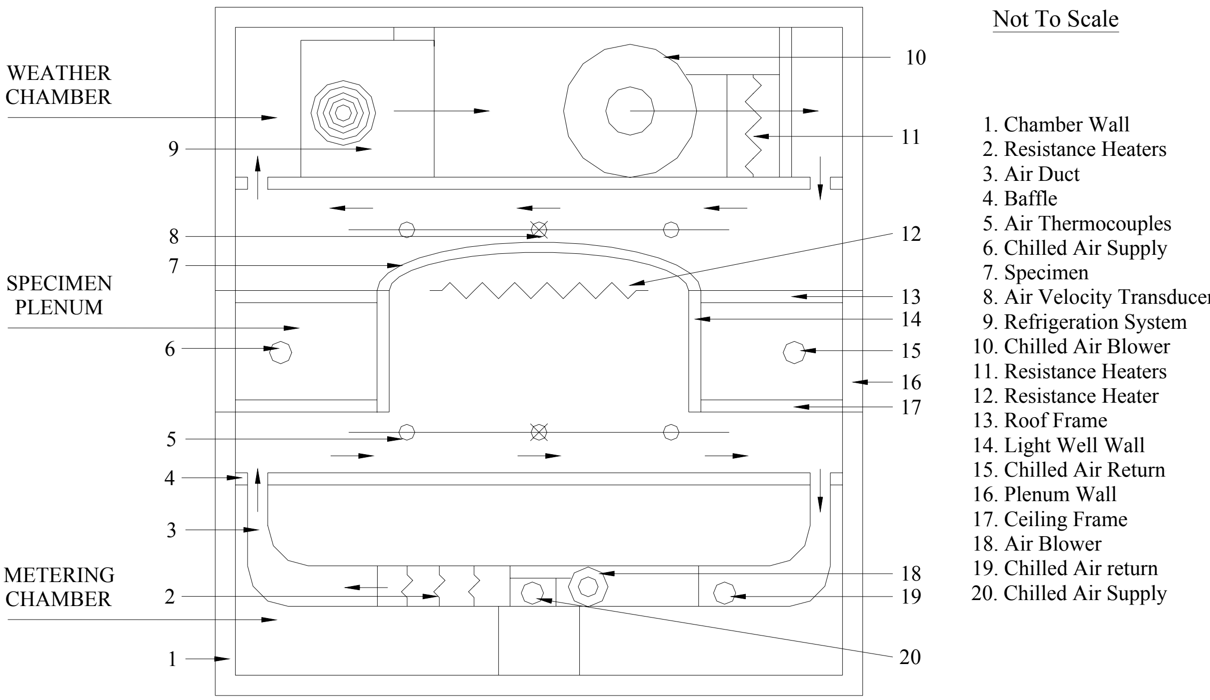

Figure 7 Vertical Heat Flow Test Apparatus for Skylight with Light Well Systems

To ensure uniform radiant heat transfer exposure of the specimen, all surfaces that can exchange radiation with the specimen have a total hemispherical remittance greater than 0.8.

4.1.4 Weather Chamber

The purpose of weather chamber is to provide forced convection air flow over the specimen surfaces and the control and measurement of the fixed conditions such as air temperatures, air velocities on the top surface of the specimen opposite the metering chamber. A centrifugal blower whose speed is controlled by a variable frequency controller is used together with small fans to circulate parallel air flow over the CTS top surfaces and/or skylight test specimen surfaces. Electrical heaters, blowers, refrigeration system, and an air circulation system are used. The chamber walls are also highly insulated.

4.1.5 Baffles

A baffle is used on both metering and weather chambers. It's a 0.5-inch thick plywood painted flat black and insulated with 2-inch EPS form boards on the back side facing the inside of the chamber. The overall dimensions of each baffle are 8-foot wide by 8-foot high. A 4 by 4 surface thermocouple grid is implemented on the painted surface of each baffle to measure baffle surface temperatures.

4.1.6 Control Plenum

A control plenum is needed when measuring a skylight with light well assembly system. The plenum is located in between the skylight support frame (roof frame) and the light well support frame (ceiling frame). It is made of highly insulated materials such as EPS foam, and controlled at the same temperatures as the metering chamber. The plenum space is surrounded by plenum walls, ceiling frame, light well walls, and the roof frame.

4.1.7 Skylight Well Construction

The skylight well is supported by the ceiling frame and constructed in accordance with the manufacturer's instruction. Characteristic measurement of skylight well material thermal conductivity will be conducted in accordance with ASTM 518 or C 177. The skylight well wall surfaces are implemented with a thermopile to measure the accumulative temperature difference across the walls.

4.1.8 Roof Frame

A specimen frame provides support to the test specimen and necessary perimeter insulation. The thickness of the specimen frame is 6-inch. Extruded Polystyrene (EPS) foam material faced with plywood or plastic is used for the frame. The frame materials will be measured in accordance with ASTM C 518 or C 177 to obtain its thermal conductivity value. The surface temperatures will be measured under steady-state conditions.

4.1.9 Ceiling Frame

1/2-inch thick drywall material is used for ceiling frame to provide support to the skylight well and plenum assembly. Characterization measurement of its thermal conductivity will be conducted in accordance with ASTM C 518 or C 177 test method.

4.1.10 Air Circulation

Air circulation system is established in accordance with ASTM C 1363 Section 6.8. The uniformity of air curtain velocity will be verified. The actual air velocity during the thermal testing is recorded.

4.1.11 Air Temperature Control

Air entering the air curtain is uniform in temperature across its width and it shall not change more than ±0.5°F during the steady-state measurement period. Both heating and cooling in both metering and weather chambers is installed to provide winter and/or summer test conditions. The air temperature in the skylight well plenum is also controlled as room condition. More detailed methods on temperature control can be found in ASTM C 1363 Section 6.9.

4.1.12 Temperature Measurement

All air and surface temperature measurements are made in accordance with ASTM C 1363 Section 6.10. Skylight well air temperature is measured at different elevations. Also the skylight well wall surface temperatures or temperature difference shall be measured.

4.1.13 Instruments

All instruments used in the test facility conform to the requirements outlined in ASTM C 1363 Section 6.12.

4.2 Vertical Heat Flow Measurement Test Chamber Setup

The setup for the vertical heat flow measurement for commercial skylight and well systems has three configurations based on three different heights of the skylight well, i.e., 1-foot, 3-foot, and 6-foot. There are also two planar skylights being set up together with 3-foot well. Therefore, in total, five configurations are designed to cover 19 tests for commercial skylights with different well systems. All the skylight specimens are installed in the roof frame in the curb-mount method as required by the manufacturers. The following sections discuss these configurations.

4.2.1 **Non Planar Skylight with One-Foot Well**

Only non-planar skylights are required to be tested together with a 1-foot well. Figure 2 shows the detail of the test setup. The skylights to be tested are curb mounted according to manufacturer’s installation guide.

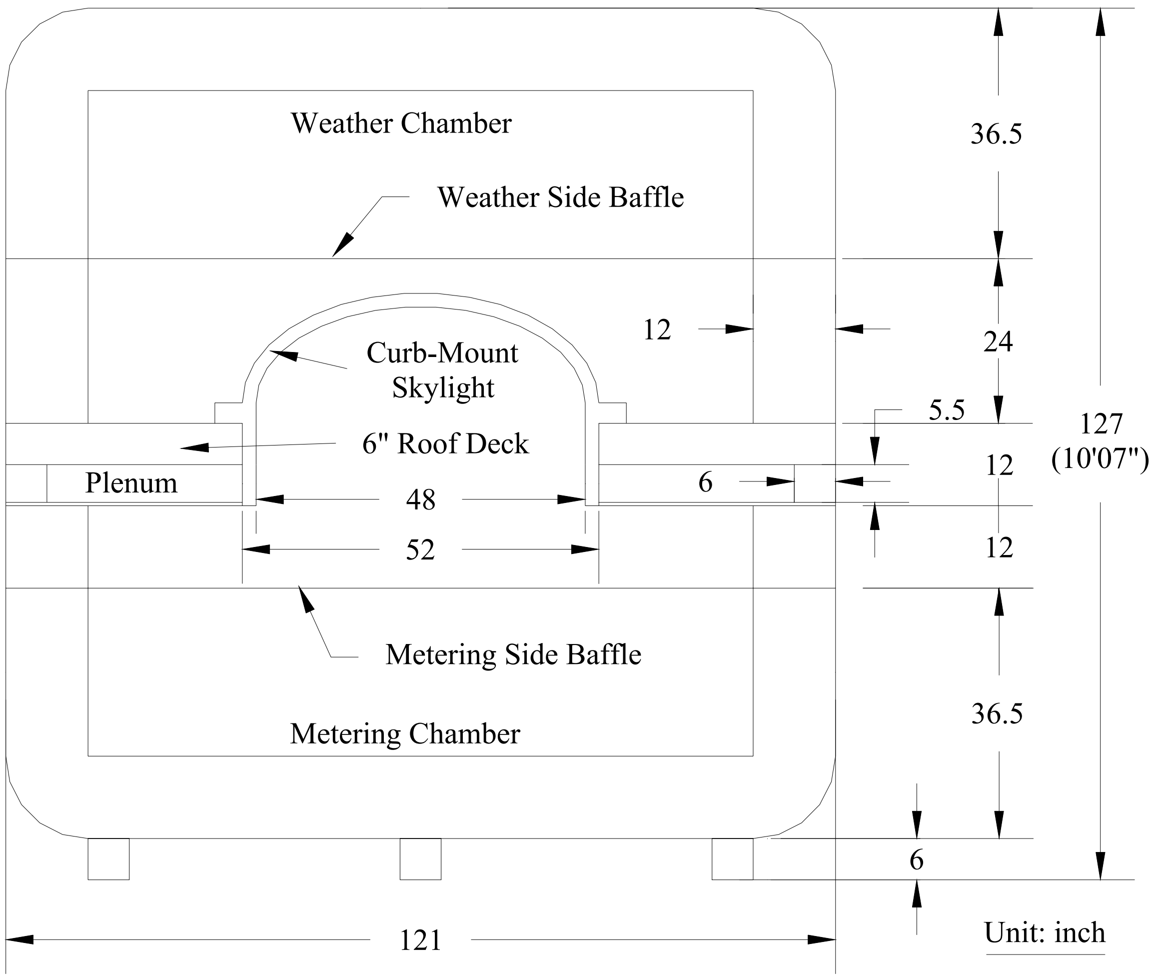

Figure 8 Test Setup for Non-Planar Skylights with One-Foot Well

4.2.2 Non Planar Skylight with Three-Foot Well

The test setup for non-planar skylights together with a 3-foot well is shown in Figure 9.

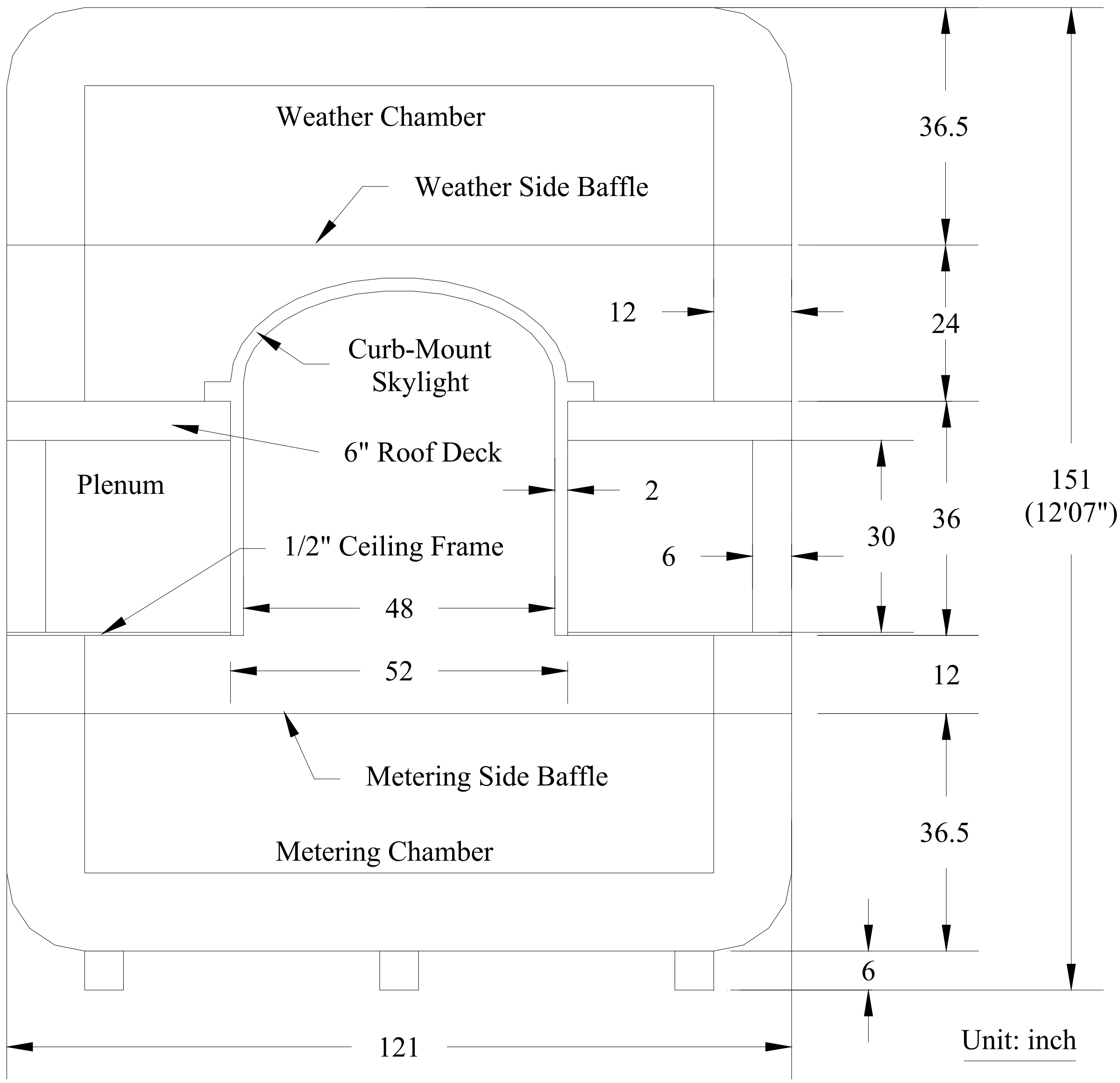

Figure 9: Test Setup for Non-Planar Skylights with Three-Foot Well

4.2.3 Planar Skylight with Three-Foot Well

The test setup for planar skylights together with a 3-foot well is shown in Figure 10. In this setup, the skylight is installed horizontally on top of the roof frame using curb-mount installation as per requirements.

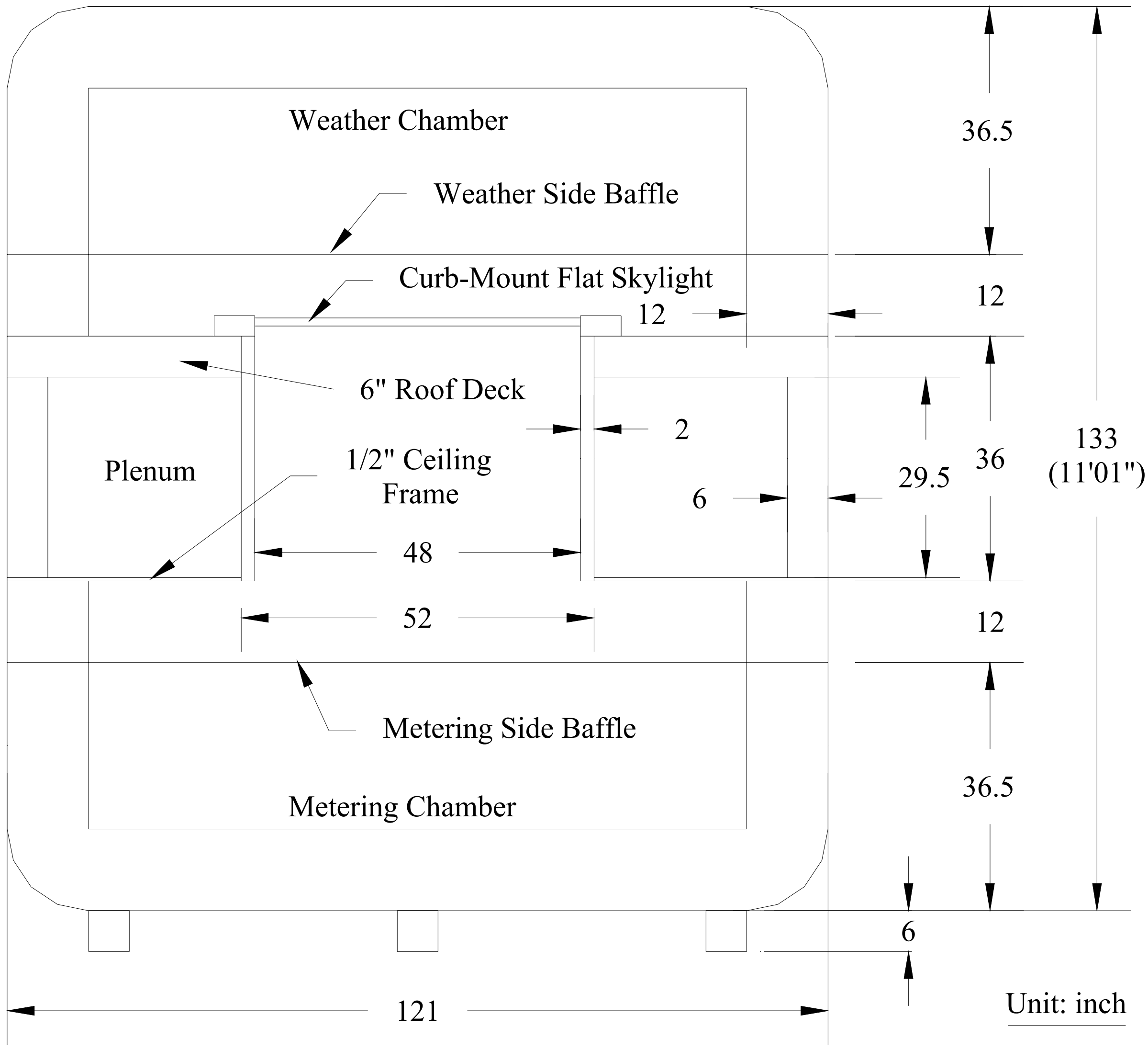

Figure 10: Test Setup for Planar Skylights with Three-Foot Well

4.2.4 Sloped Planar Skylight with Three-Foot Well

The test setup for sloped (20° to horizontal) planar skylights together with a 3-foot well is shown in Figure 5. In this setup, a curb-mount wood frame is used to install the planar skylight at a 20° angle to horizontal. The wood frame is installed on top of the roof frame as shown in Figure 11.

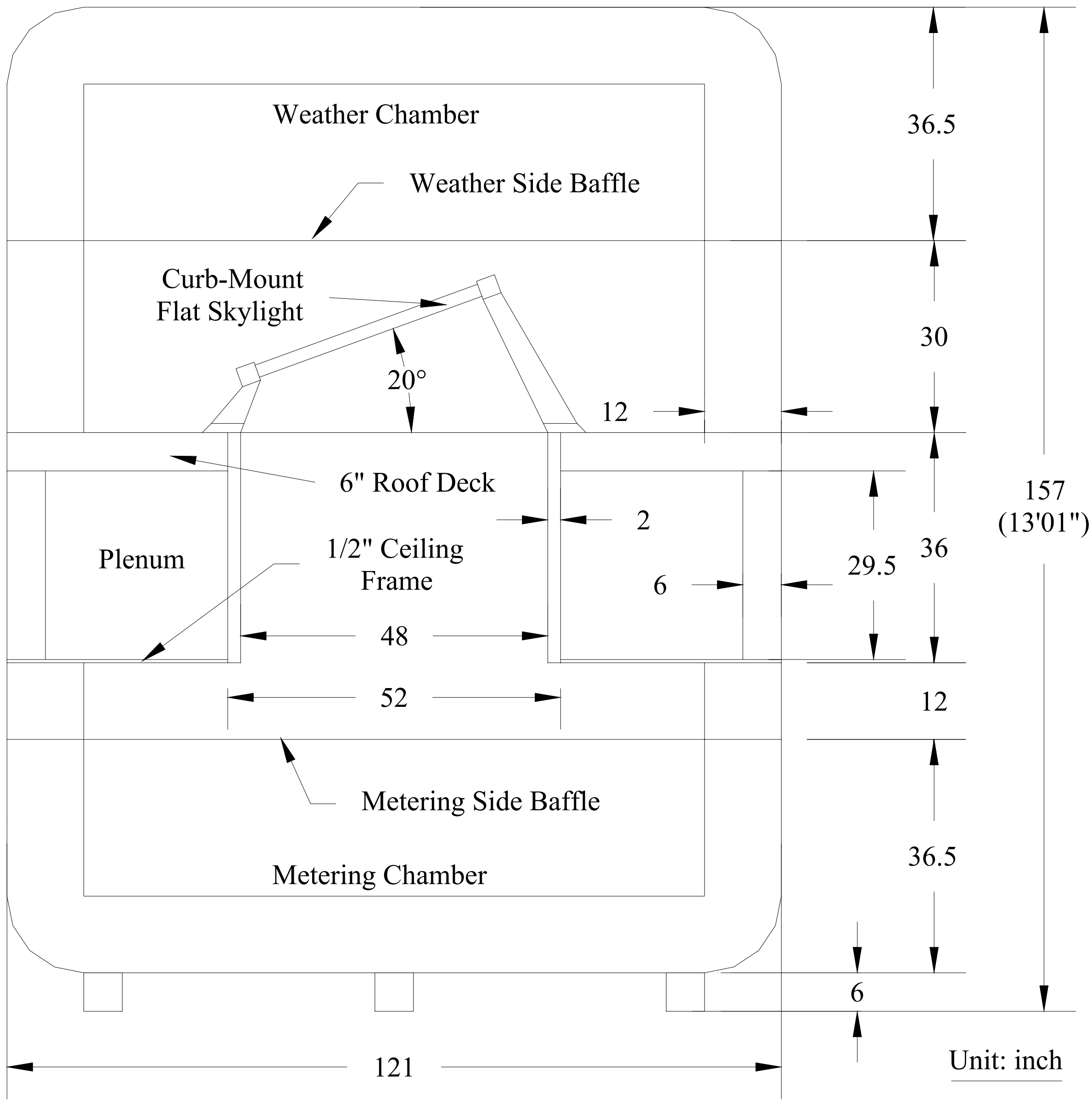

Figure 11: Test Setup for Sloped Planar Skylights with Three-Foot Well

4.2.5 Non Planar Skylight with Six-Foot Well

The test setup for non-planar skylights together with a 6-foot well is shown in Figure 12. In this setup, the only difference from Figure 9 is the well height.

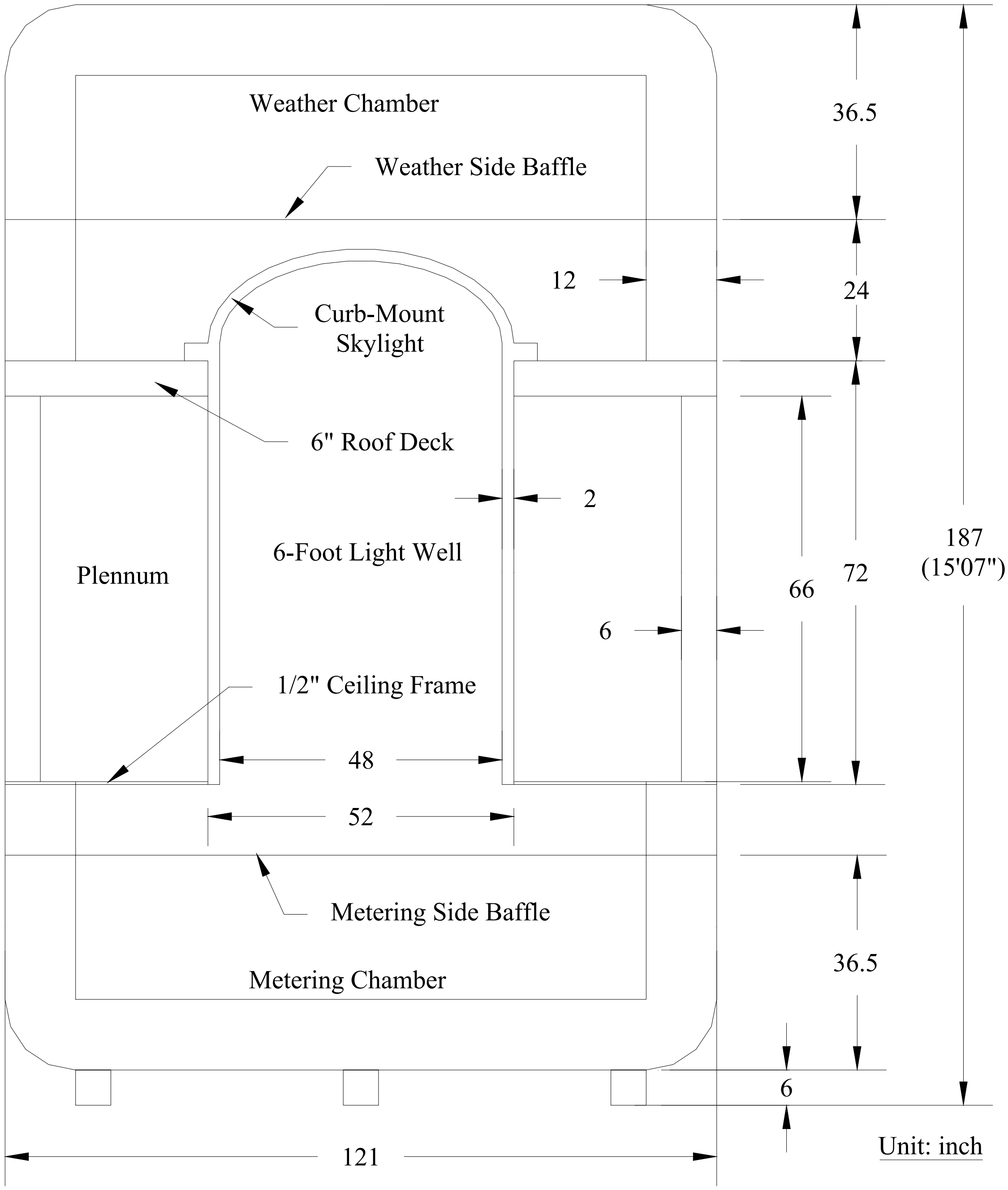

Figure 12: Test Setup for Non Planar Skylights with Six-Foot Well

P500-03-082-A-27

Summary of U-Value Test vs. Model (product 5.3.2b)

Not yet complete

Please check the website in December 2003 for this document

P500-03-082-A-27

Summary of SHGC Test vs. Model (product 5.3.3b)

Not yet complete

Please check the website in December 2003 for this document

P500-03-082-A-27

Summary of VLT Test (product 5.3.4)

Is now merged with
Summary of FLT Angle Test vs. Model (product 5.3.4b)

Visible Light Transmittance of Skylights

by
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Heschong Mahone Group

October 2003

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About PIER

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission, annually awards up to $62 million to conduct the most promising public interest energy research by partnering with research, development and demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

1. Buildings End-use Energy Efficiency
2. Industrial/Agricultural/Water End-use Energy Efficiency
3. Renewable Energy
4. Environmentally Preferred Advanced Generation
5. Energy-Related Environmental Research
6. Strategic Energy Research.

This project contributes to the first topic area, the PIER Buildings Program Area. For more information on the PIER Program, please visit the Commission's Web site at: www.energy.ca.gov/pier or contact the Commission's Publications Unit at 916-654-5200. For other public reports within the *Integrated Energy Systems — Productivity and Building Science* project, please visit www.newbuildings.org/PIER.

The HESCHONG MAHONE GROUP has produced this report as part of the Integrated Design of Commercial Building Ceiling Systems research element of the *Integrated Energy Systems - Productivity and Buildings Science* energy research program managed by the New Buildings Institute. Cathy Higgins is the Director of this project for the New Buildings Institute.

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Legal Notice

Foreword

This research in this report has been designed to support the Integrated Design of Commercial Building Ceiling Systems research element. This research project consists of three related components:

1. Effectiveness of lay-in insulation
2. Comprehensive skylight testing
3. Culminating in a modular skylight well protocol for suspended ceilings that provide quality lighting (including daylight) and energy savings.

This report describes the measurement of skylight glazing transmittance and the effective visible transmittance of the skylighting system (skylight, light well, diffuser etc.) and the relationship between the two.

The purpose of this research element is to provide basic research input into a protocol for designing and specifying highly efficient ceilings that will incorporate effective placement of insulation, daylighting via toplighting and daylight-responsive electric lighting controls. This protocol is contained in the California Energy Commission design guideline titled, *Modular Skylight Wells: Design Guidelines for Skylights with Suspended Ceilings*.

Adoption of this protocol may lead to greater use of skylighting in conjunction with daylighting controls. Widespread use of skylighting with daylighting controls is estimated to have a significant impact on the energy consumption of commercial buildings.

EXECUTIVE SUMMARY

This report describes the visible transmittance testing of skylight glazings and the two different methods of testing the overall effective visible transmittance of skylighting systems (skylight, light well, diffuser etc.). This data can be used to validate skylight transmittance models and develop new ones. Ideally these models ultimately impact both building energy and lighting simulation programs as well as the systems developed to rate the performance of skylights.

The primary finding of this study is that *both the visible transmittance of the glazing and the skylight shape affect the transmittance of the skylight*. This is especially important when we compare the effective visible transmittance of the skylighting system at the relatively low solar elevation of 30º, the angle that the sun is most frequently near for most of the hours during the year.

Flat skylights have a noted drop off in effective visible transmittance at 30º solar elevation as compared with normal incidence visible transmittance (90º solar elevation). In comparison, dome skylights have a visible transmittance that is relatively constant regardless of solar angle. Thus a rating system that was based upon normal incidence would overestimate the performance of flat skylights during much of the year as compared to dome skylights.

The existing NFRC (National Fenestration Rating Council) test protocols limit the visible transmittance rating of skylights to those with flat non-diffusing glazings. However, these type of skylights are but a small fraction of the unit skylight market for commercial buildings. It is suggested that the NFRC consider a test method that can be applied to any shape and material of skylights and that they consider a simulation program (such as NRC Canada's SkyVision) that can simulate the visible and solar heat gain performance of projecting skylights and TDD's (tubular daylighting devices). The need for such a test method and modeling method is quite imperative in that if everything else is equal, including normal incidence visible transmittance, the projecting skylight will yield greater energy savings.

When skylights are used to displace electric lighting, they must have a means for diffusing daylight so that it is a useful source of light and not a source of glare. This project has identified a simple, inexpensive test that can identify on a gross level the level of diffusion from glazings. This test is the haze test administered in accordance with ASTM D1003. When glazing haze is greater than 90%, the glazing is considered to be relatively diffusing. This metric is useful to code developers and lighting designers when specifying a skylighting system that is intended to displace electric lighting.

INTRODUCTION

The primary purpose of skylights is to bring daylight into the interiors of buildings while keeping moisture out. As such the visible transmittance of skylights is of high importance when selecting skylights.

Approximately 60% of commercial buildings have a suspended ceiling between the roof and the occupied space. When buildings are designed with both skylights and suspended ceilings, a passageway from the skylight to an opening in the ceiling plane, called a light well, allows the light to enter into the room. Thus, the skylight does not work in isolation, the geometry and reflectance of the light well affects the overall luminous performance of the skylighting system.

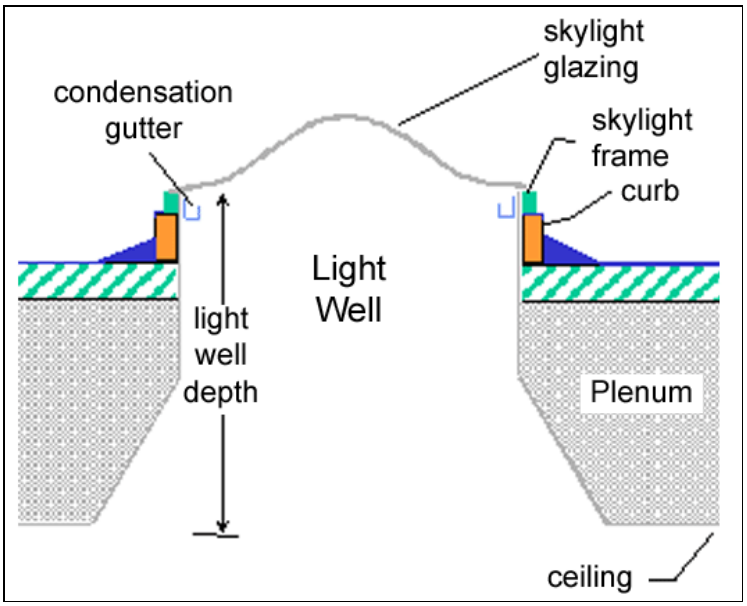


Figure 1: Skylight with Light Well

This report describes the testing of several types of skylights, their glazing and skylights with light wells. Commonly used calculation methods are compared with the test results. This comparison can help the designers in selecting the best methods for comparing skylighting system performance.

Economic Impact of Skylights with Suspended Ceilings

A casual observer might wonder why the performance of skylights is of interest to the Public Interest Energy Research (PIER program). The short answer is skylights installed with the appropriate lighting controls result in substantial reductions in electric lighting energy consumption. Table 1 illustrates the potential energy cost savings in California from installing skylights and lighting controls in five building types. (McHugh et al 2003c) This estimate considers only the fraction of spaces that are directly under a roof, have suspended T-bar ceilings and where adding skylights are feasible. This table shows that one year's worth of new and retrofit construction would save California ratepayers approximately $3.2 Million, or after 10 years the ratepayers would be saving $32 Million per year!

Table 1: Feasible Energy Cost Savings Potential from One Year's New/Retrofit Construction for 5 Selected Building Types

Occupancy	New or Retrofit M SF/yr	Under Roof	T-bar Ceiling	Feasible	Total Million SF/yr	$/SF-yr	Annual Savings ($Millions)
Lg Office	30.9	35%	45%	50%	2.4	$ 0.15	$ 0.4
Sm office	9.9	50%	45%	50%	1.1	$ 0.15	$ 0.2
Grocery	6.6	100%	46%	75%	2.3	$ 0.23	$ 0.5
Retail	24.8	80%	46%	75%	6.9	$ 0.23	$ 1.6
Education	12.6	60%	68%	75%	3.9	$ 0.16	$ 0.6
Totals	**84.8**				**16.5**		**$ 3.2**

The above estimate is only for low rise buildings with suspended ceilings. However, this research on visible transmittance of skylights impacts skylighting systems in all building types – even those without suspended ceilings such as big box retail and warehouses. Approximately 60 Million sf of new warehouses and big box retail is added to the California building stock per year. Thus the total impact of skylighting is two to three times the estimate of the impact on buildings with suspended ceilings or as much as a $100 Million/yr savings after ten years of aggressively adding skylighting to commercial construction.

However, the energy cost savings impacts may be but the tip of the iceberg in terms of the economic benefits of greater use of skylighting. As shown above the energy cost savings from daylighting are between $0.15/SF and $0.23/SF. In contrast, the salary and overhead costs of office workers range from $100 - $400/SF. A study found the average salaries and overhead of Federal government workers to be around $165/SF (Harris et al. 1998). Annual retail sales are of a similar magnitude; the average annual sales for non-food retail is $153/SF of floor area and for supermarkets $490/SF of sales floor area (Food Marketing Institute 1999). Thus, building features that can reliably increase human performance or retail sales even 1 percent would have around a $1.50/SF to $5.00/SF impact on sales or office labor costs. The effect of increases in productivity or sales on profits would vary by industry.

Recent reports on the value of daylighting have correlated full daylighting to 21% higher test scores in schools (HMG 1999a) and 40% increases in retail sales (HMG 1999b). Thus there is growing evidence that daylighting is linked to a probability of higher productivity in different work environments. In addition, the magnitudes of the productivity gains indicate an economic impact on profits that are as large or larger than the energy cost savings impact of daylighting. To the extent that these effects are related to building occupants receiving daylight, this result highlights the importance of being able to predict the amount of light transmitted by the skylight and light well system.

Focus on commercial buildings

When calculating the energy savings impact of skylights in Table 1, all of the occupancy types were nonresidential. This exclusion of residential skylighting is due a qualitative difference between residential and commercial skylighting. Commercial and industrial occupancies are good targets for energy savings from skylights since they have high lighting power densities, extensive lighting use during daytime hours, and whole building energy consumption that is relatively insensitive to envelope thermal transmittance (U-factor). Residential buildings, on the other hand, are not likely to see energy savings from skylights for the opposite of all the reasons listed above.

This qualitative difference in residential versus commercial skylighting results in different products being used; residential skylighting relies on a substantially greater fraction of flat glass skylights than commercial skylighting which uses plastic dome skylights. A tabulation of the differences in commercial and residential skylighting in Table 2 illustrates factors that have driven commercial skylighting toward diffusing plastic domes and residential skylighting towards clear flat glass glazing.

Table 2: Differences between Commercial and Residential Skylighting

Topic	Commercial Skylighting	Residential Skylighting
Energy	Displace electric lighting	Reduce heat loss and gain
Roof slope	Often flat roof	Often sloped roof
Profile	Profile not important	Low profile desired
Clarity	Diffusion desired for glare control	Often clear for view of sky
Cost	Must be cost-effective	Aesthetic amenity

Glass is more expensive than plastic, but it can accept low-e coatings, which reduce both heat gains and losses, and flat glass skylights have a lower profile than domes, which are projecting. Dome skylights can be placed on flat roofs without requiring a slanted curb or adapter. As will be quantified later on in this report, dome skylights are better at intercepting low angle sunlight.

Importance of Light Transmittance to Skylight Performance

Understanding the luminous performance of skylighting systems is of great importance because these systems have the potential to substantially increase California's economic efficiency. The most evident benefit of skylighting is the energy savings that can be realized by reducing of lighting energy consumption and cooling loads in commercial buildings. This benefit is realized when photocontrol systems are used in conjunction with skylights. Photocontrol systems measure the amount of light inside of a space and turn off or dim electric lights during peak daylight hours while maintaining as much or more light than the design light levels. Cooling loads can go up or down depending upon the trade-offs between less internal gains from electric lights and increased solar gains or thermal conduction through the skylights. Heating loads are almost always increased by skylights due to increased thermal conduction of the roof and reduction in electric lighting internal gains.

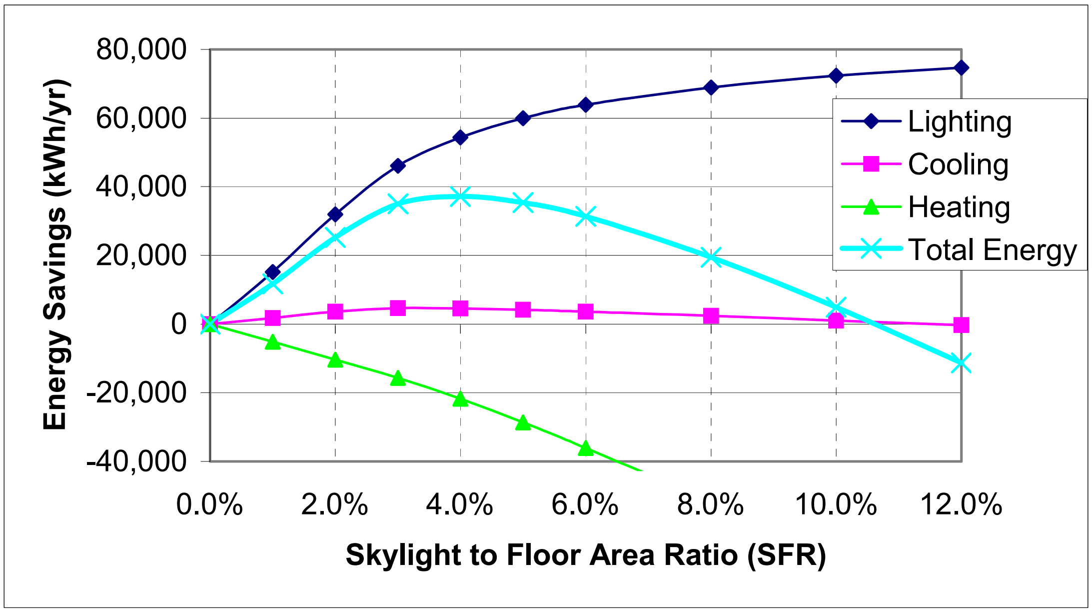


Figure 2. Components of energy savings due to skylights[1].

Figure 2 illustrates the results of a SkyCalc calculation of the components of energy savings resulting from adding skylights and a photocontrol system to a 25,000 square foot retail store in San Francisco, CA. Energy savings are described in relation to the skylight area to floor area ratio (SFR) of double glazed plastic skylights. It should be noted that one of the key assumptions in SkyCalc is that the skylights are perfectly diffusing and that they are spaced for relatively uniform illuminance (typically no further apart than 1.5 times the ceiling height). Lighting energy savings increases as more skylights are added, cooling savings increase at first but after 3%, decrease as additional skylights add more solar heat than the reduction in heat from electric lighting. Overall energy savings are maximized at 4% skylight to floor area ratio. The optimum energy savings varies by climate, occupancy type, lighting power density etc., but the main point illustrated by this figure is that the primary benefit from skylighting is bringing in enough daylight to turn off or dim electric lighting.

[1] Figures calculated using SkyCalc®, a skylight design simulation software developed by the Heschong Mahone Group. A copy of the program can be accessed from http://www.h-m-g.com or through the NBI PIER website.

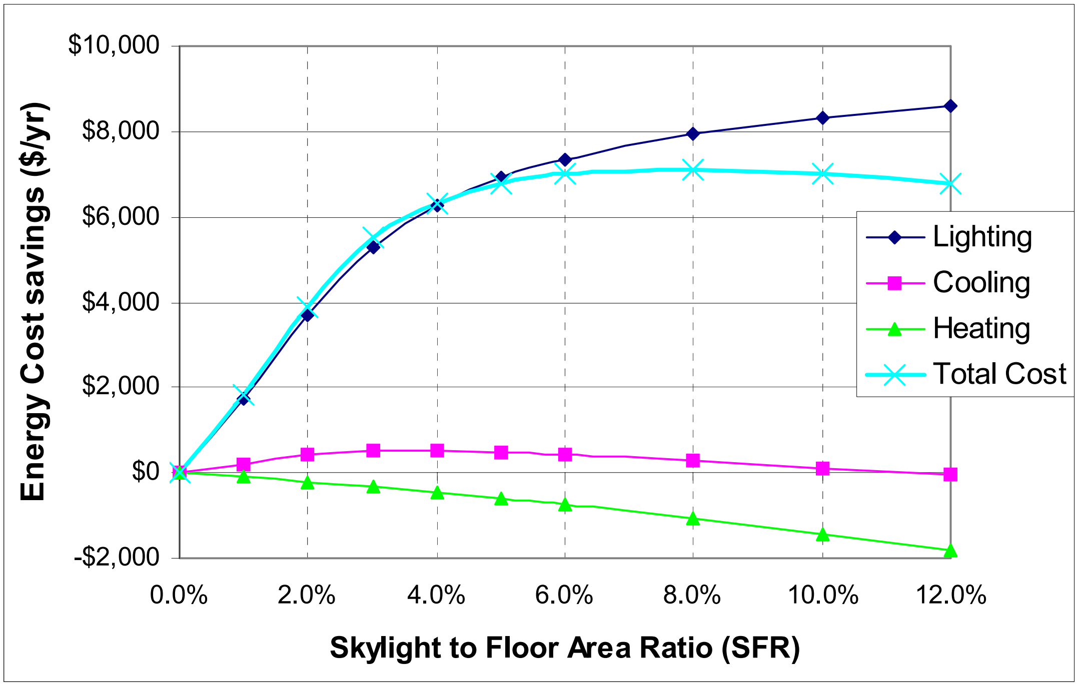


Figure 3. Energy cost savings due to skylights[2].

Figure 3 illustrates the components of energy cost savings as natural gas rates are applied to heating energy and electricity rates are applied to lighting, and cooling. In California, the gas costs per unit of energy are approximately a fifth of the cost of electrical power; this results in the heating losses though relatively large having as small impact on the overall cost savings from an optimal skylighting system with a 6% skylight to floor area ratio. The primary lesson to be learned from this is that the key parameter of a skylighting system is how well it can deliver daylight so that electric lighting can be turned off. The secondary lesson is that heat losses are less important in California's mild climates and with the substantial cost differences between electricity and natural gas.

Importance of Diffusion to Skylight Performance

For the proper design of daylighting in workspaces, such as schools or offices, it is essential that light quality be diffusive. Non-diffusing light sources, whether they are electric lights or skylights, will cause excessive glare on the task surface and cause visual discomfort for the occupants.

Diffusely transmitting skylight systems distribute light across a wider area, thus requiring fewer skylight installations. They also result in less "hot spots" within the space that might cause thermal discomfort for the occupants. (See Figure 4).

[2] Figures calculated using SkyCalc®, skylight sizing software developed by the Heschong Mahone Group. A copy of the program for California cities can be accessed from http://www.energydesignresources.com for additional climates go to http://www.h-m-g.com

If skylights are going to be used to displace electric lighting it is important that they are sufficiently diffusing.

Figure 4. Clear skylight with “hot spot” and diffuse skylights with even lighting

Skylight Visible Light Transmittance and Well Efficiency

Overall visible light transmittance of the combined skylight and light well system is a product of the visible light transmittance of the skylight and the transmittance of the light well, called the well efficiency.

The visible transmittance of a product is the fraction of light from the sun that passes through the product. To measure visible transmittance, only the fraction of solar radiation within this “visible” wavelength on the surface of the glazing material or passing through is considered.

$$T_{vis} = \frac{\textbf{Light passing through glazing}}{\textbf{Light incident on glazing}}$$

Visible light transmittance is usually tested with the incident light "normal" or perpendicular to the glazing material. Calculation models are then used to estimate transmittances at other incident angles. A simplifying assumption is that the skylight glazing is flat and thus transmittance decreases at lower solar elevations. This report will investigate the error that results when this assumption is applied to domed and other projecting skylights.

The well efficiency, WE, is the fraction of light that is transmitted by the light well and is given by the relation:

$$\mathbf{WE} = \frac{\textbf{Light exiting bottom of light well}}{\textbf{Light entering the top of light well}}$$

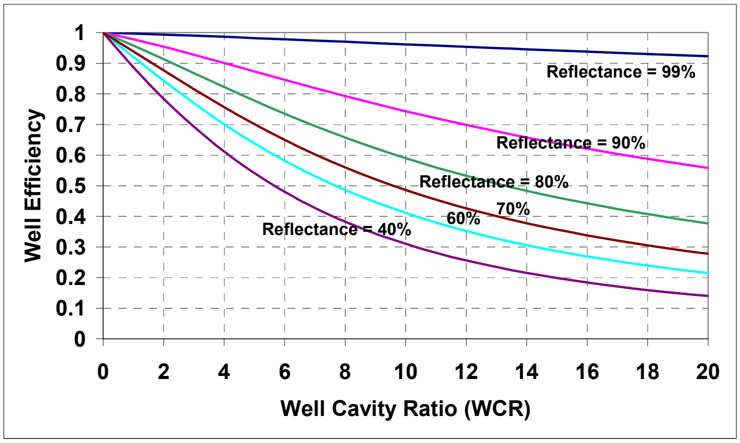


Figure 5: Well efficiency as a function of well cavity ratio and reflectance

For light wells that are under diffusely transmitting skylights and have diffusely reflecting surfaces, the well efficiency can be calculated using the Lumen Method. The IESNA Handbook publishes a well efficiency graph that is a function of the well geometry (well cavity ratio), and the average well surface reflectance. The well cavity ratio, RCR, is given by the equation below, where, well perimeter and well area are measured at the bottom of the light well.

$$\mathbf{WCR} = \frac{\textbf{2.5} \times \textbf{well height} \times \textbf{well perimeter}}{\textbf{well area}}$$

The graph of well efficiency shown in Figure 5, is based upon a Lumen Method calculation with a top of cavity reflectance of 99% and a bottom of cavity reflectance of 0%. (Heschong & McHugh 2000) This matches closely the well efficiency figure published in the IESNA handbook.

If the well efficiency nomograph were applied to light wells with specular (mirror-like) surfaces, the resulting well efficiency estimate would be lower than its actual performance. The performance of such light wells is best estimated using an alternate calculation method. Since tubular skylights typically make use of a specular light well, further discussion of the methods used to calculate specular light well efficiency are contained in the section on "Transmittance of Tubular Daylighting Devices (TDD's)"

Existing Light Transmittance Testing and Modeling Methods

As described above, the key determinant of the energy performance of a skylighting system is its ability to transmit useful energy from the outdoors to where tasks are being performed. To predict how much useful light makes it from the outdoors to the task requires reliable methods of measuring the physical properties of skylighting system components and a method of calculation that results in fidelity to real results.

The definition of "useful light" is a function of both is quantity (lumens) and its quality (distribution). The total quantity of light entering the room through a skylight and light well is the product of the skylight visible transmittance and the well efficiency. The distribution of light can be approximated by two different methods, measurement of glazing diffusion or by photometric measurements of the skylighting system. A companion report also created for the PIER program describes photometric testing in detail.[3] However, this report will touch upon the measurement of glazing diffusion and will also make use photometric measurements as they relate to measurements of total quantity of light admitted though the skylight/light well system.

NFRC 300: Solar Optical Properties of Glazing Materials and Systems

The National Fenestration Rating Council (NFRC) has adopted a procedure for determining Visible Transmittance (VT) for simple fenestration products. The visible transmittance of a fenestration product is rated at an incidence angle of 0º degrees, or normal to the flat glazing surface. It does not cover strongly diffusing materials, patterned or textured materials, complex glazing like prismatic panels, and curved skylights.

The NFRC test method is based upon solar optical measurements using a spectrophotometer equipped with an integrating sphere as described in ASTM E903. These test measurements of individual glazing layers are then combined together to form the overall skylight transmissivity using the LBNL Window 5 program or as calculated using the equations contained in the NFRC 300 test method.

The benefit of taking measurements in an integrating sphere is that the sphere "integrates over all transmitted angles" that is captures light leaving the sample in all directions and measures the total transmitted light. Thus it may seem incongruous that the NFRC 300 method does not allow diffusing glazings to be tested according to this method. The reason for this prohibition is that the calculation methods embedded in the LBNL Window 5 program and in the test method assume that for multiple layer glazings the path of light remains unaltered as it is transmitted through the glazing assembly. This is important as both reflectance and absorptance vary with respect to angle. *If this is the only reason for the prohibition on strongly diffusing glazing, the prohibition should be reduced so that it only applies when the diffusing glazing is not on the bottom (inside) layer.*

Both the NFRC-300 calculation method and the LBNL WINDOWS model represent the performance of a flat glazing surface with a single angle of incidence over the entire skylight surface. Thus neither of these methods will

[3] Jon McHugh, *Skylight Photometry Test Methods and Results*, PIER Report for Contract Number 400-99-013, June 2003

accurately predict the performance of any projecting skylight (domes, pyramid, catenary arch etc.). Doming causes the angle of incidence of the direct sunlight to vary over the dome's surface, and increases the light gathering surface area than a flat sheet.[4]

Thus the NFRC-300 standard test method cannot be used to rate the visible transmittance of the most popular commercial skylighting product – domed plastic skylights. This is particularly troublesome in that projecting skylights have better transmittances than flat skylights when the sun is low on the horizon and yet there is no NFRC test method to capture this effect.

NRC – SkyVision

The inability of the LBNL Window 5 program to model projecting glazing has been a major obstacle towards an NFRC rating of projecting skylights. The National Research Council Canada has been working on a visible light transmittance and solar heat gain transmittance simulation tool for projecting skylights called SkyVision (Laouadi et al. 2003). This software is currently in a Beta (draft) version. It may be that SkyVision or its algorithms may play a role in getting past the current simulation roadblock for projecting and diffusing skylights.

Transmittance of Tubular Daylighting Devices (TDD's)

Tubular daylighting devices typically have a clear hemispherical dome on top of a specularly reflecting tubular light well which terminates at a round diffuser or a round to square adapter and a square diffuser at the ceiling level. The benefits of these devices are:

- Light well can be offset easily to get around obstructions using the same type of angle adapters used for circular vent pipe.
- Roof flashing is well developed – the design is similar to "roof jacks" used to flash piping penetrations in roofs.
- For the relatively high roof cavity ratios encountered in tubular skylights, well efficiencies are kept relatively high by the use of specular reflecting materials with high reflectances. Advances in material science have made it possible to have specular reflectivities very close to 100%. (Weber et al. 2000)
- Labor costs can be reduced by prefabricated light wells and curbs. This has a trade-off with the increased number of roof penetrations needed to provide the same aperture area as larger square unit skylights.

There has been a desire to rate the overall transmittance of the entire TDD assembly as the TDD is sold as a single product. In addition, traditional well

[4] IESNA Handbook, 9th ed., p. 8-11.

efficiency calculations based upon the lumen method would underestimate the well efficiency of TDD's.

In response to this need, a draft of NFRC 202 "Calculation of Tubular Daylighting Device SHGC and T_{vis}" contains a proposal for rating the solar heat gain coefficient (SHGC) and visual transmittance of tubular daylighting devices based upon a calculation method. This calculation method is based upon the solar optical transmittance of the top glazing and bottom diffuser materials and the solar and visible reflectance properties of the surface of the tube. No testing of the overall transmittance of a representative system is required to calibrate the results.

This calculation method is limited to tubular skylight systems with the following properties:

- hemispherical skylights with curvature within ±10%
- limited to a specific zenith angle of 30°, which is a solar angle of 60%
- insignificant diffusion of glazing
- specularly reflective tubular light well

This calculation method does not cover TDD's with top domes that have a significant reflecting or lensing systems, or systems with light wells having a diffuse reflectance greater than 5% of specular reflectance.

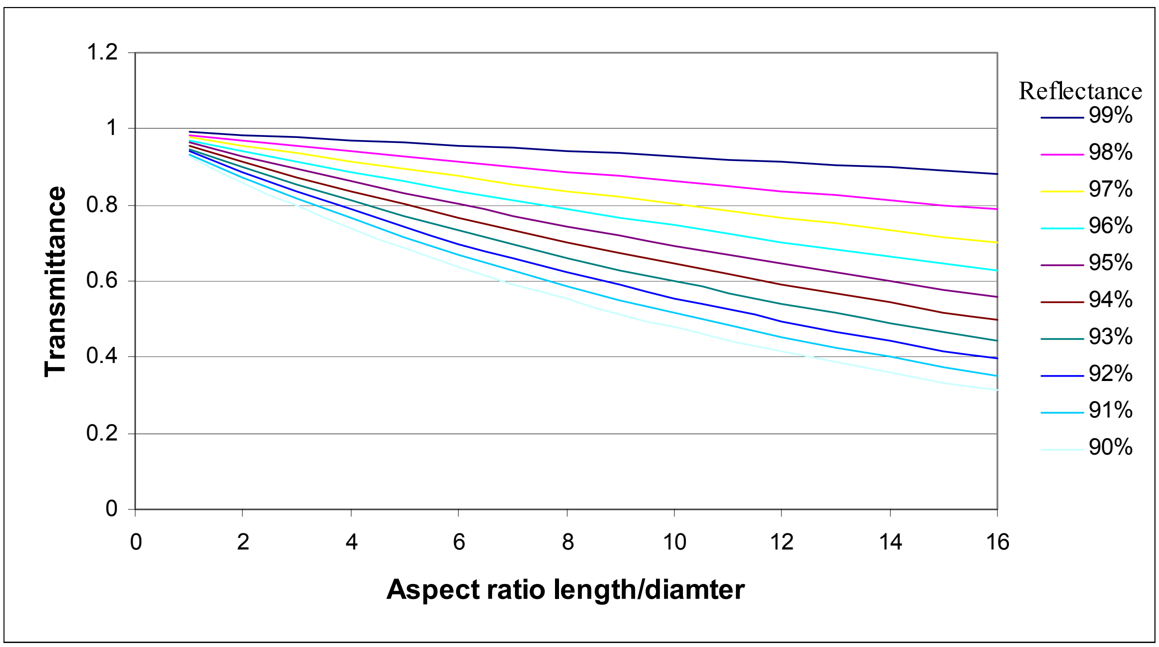


Figure 6: NFRC 202 reflective tube transmittance (30° incidence)

Total system transmittance is the product of transmittance of skylight, well and diffuser. Transmittances of the skylight glazing and diffuser are measured from planar sheets of the glazing material, with calculations accounting for curvature of the top dome. The transmittance of the tubular well is based upon ray tracing simulations for different material reflectances and different aspect ratios of tube diameter to length.

The equations and ray tracing simulations in this draft NFRC standard for TDD's assume a direct beam solar incidence angle of 30°, or for a horizontal TDD, a solar altitude of 60° above the horizon. From discussion with the author of the draft standard, this incident angle was chosen because at this high sun angle the performance of TDD's with reflectors or refractor devices on the bottom third of the dome is similar to those without such devices.

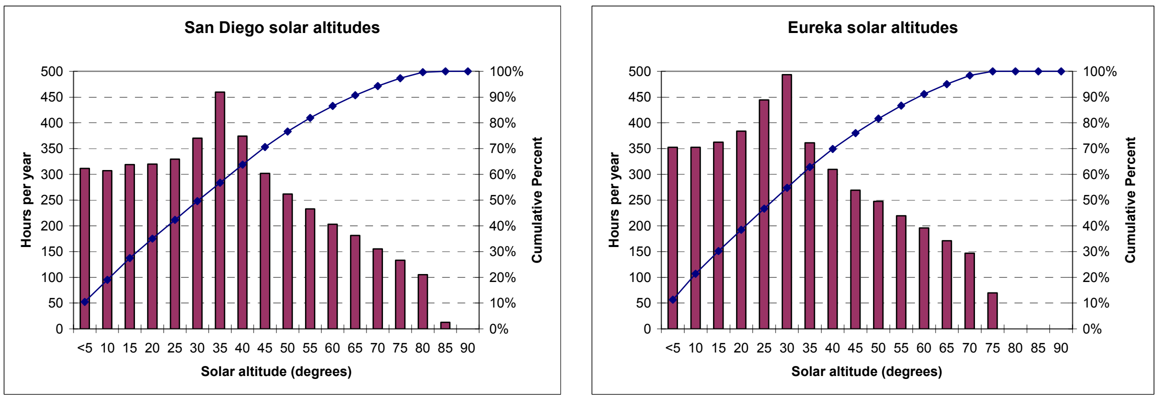


Figure 7. Frequency of solar altitudes in San Diego, CA and Eureka, CA.

However, as shown in Figure 7 for San Diego in the southern tip of California to Eureka on the northern end of California, the most common solar elevations over the course of the year are in the range of 10° to 40°. Using the NFRC performance ratings based upon a 60° solar altitude overestimates the light transmittance of tubular daylighting devices for most of the hours in a year.

How much greater is the visible transmittance of a light pipe with the assumption of a 30° incident angle of as compared to the more sun common angles experienced during the year such as 60° angle of incidence (30° solar altitude)? Smith and Swift (1995) have developed an analytical solution to the transmittance of tubular light pipes and validated this work with measurements of transmittance of light pipes using a Helium Neon laser as the collimated light source and an integrating sphere to measure the exiting luminous flux. Figure 8 shows variability in transmittance of a cylindrical light pipe having a 95% reflectance with respect to the incident angle of light and the characteristic aspect ratio, p, of length divided by diameter. When the length of the tube is 6 times greater than its diameter, the transmittance at 30° incident angle (60° solar altitude) is 50% greater than at a 60° incident angle. Thus the tube efficiency is lower than the rated amount 85% of the hours in the year.

It is also worth noting that for an aspect of ratio of 6 with a 95% reflectivity, Smith and Swift predict a transmittance of 65% whereas the NFRC 202 standard predicts 80% transmittance. The differences between these two estimates should be reconciled if this rating method is to be pursued.

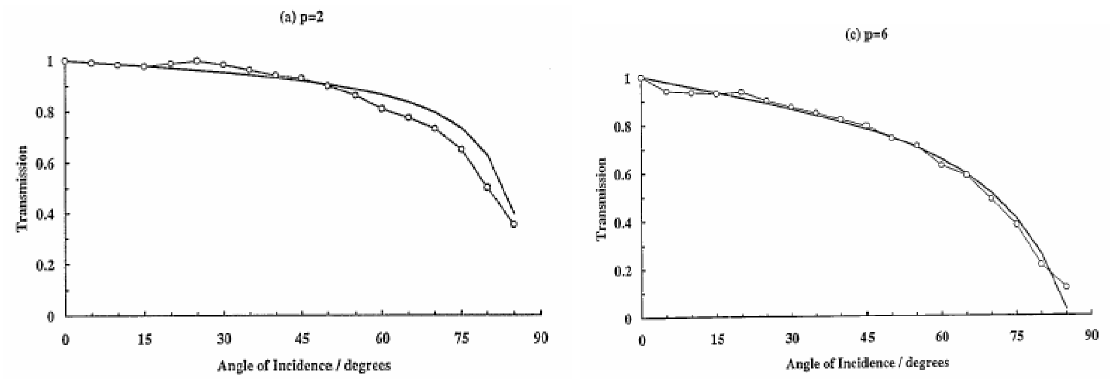


Figure 8: Light pipe transmittance as a function p (l/dia.) and angle of incidence

(Source: Smith & Swift 1995)

Thus this proposed rating method does not provide information regarding the skylight's performance during the more frequently occurring solar elevations when daylight availability is lower, and thus, requiring higher levels of light transmittance from the skylight products. The calculated overall transmittance of a diffusing skylight over a diffusely reflecting light well is the product of the skylight glazing transmittance and the light well efficiency. As we will see later, the transmittance of dome skylighting is fairly constant over the course of a day and if sufficiently diffusing, the light well efficiency will also remain constant. Thus the TDD rating which overestimates its transmittance for most of the hours of the year does not provide a comparable metric to that of unit skylights when combined with diffusing light wells. This rating system is bound to cause confusion to specifiers when comparing between different skylight types.

Existing Skylight Design Simulations

DOE-2 and Window 5 Software

DOE-2 is a whole building energy analysis program that can model daylighting, daylighting controls, building space conditioning loads and the energy consumption of building environmental systems (lighting, HVAC and appliances). To calculate the energy savings from daylighting, DOE2 must make the following calculations:

- Total amount of visible light incident on the glazing and the angle of incidence from weather file and geometric model.
- Visible transmittance of daylight with respect to angle of incidence from glazing library or internal calculations.
- Fraction of light transmitted through glazing that illuminates the reference task position in the zone from geometric model of zone (Winkelmann 1983). This uses the "split-flux" calculation algorithms in DOE-2 and models the distribution of light through a glazing as either perfectly specular (clear) perfectly diffusing (Lambertian). One can also create sun position specific

daylight factors, import this into DOE-2 and DOE-2 will interpolate between these daylight factors by sun angle and sky condition to simulate interior daylight availability over the course of a year. [5].

- Reduction in electric lighting energy, based upon the electric lighting control strategy and setpoint.

DOE-2.1E calculates the angular transmittance of glazing in two ways:

1. For a few glazings, the angular transmittance is calculated as a cubic polynomial in the cosine of the solar incidence angle. The coefficients in this polynomial are a function of the glass type and number of panes. This method is a legacy of older versions of DOE-2 and is based on the assumption of flat homogenous glazing layers.
2. Most of the glazings are contained in a glazing library, which contains angular transmittances pre-calculated by the WINDOW[6] program. This program can convert normal incidence transmittances into angular transmittances based on the assumption of flat glazing (Rubin et al. 1988).

DOE-2 is the simulation engine for many other building energy simulation programs including Energy10 and VisDOE. The skylight sizing spreadsheet SkyCalc adjusts pre-calculated DOE-2 simulations and thus has an angular transmittance model that is also based upon flat perfectly diffusing glazing.

The compliance software for the Alternative Compliance Method (ACM), California's building efficiency standards (Title 24) is currently EnergyPro. EnergyPro though based upon DOE-2 does not calculate daylight availability for calculating energy savings from daylighting controls but rather reduces the installed lighting power density (LPD) as a function of the effective aperture of the glazing systems.

Radiance

Radiance is a ray-tracing computer program that can model just about any material surface that one can create a probabilistic function of its behavior. (Ward 1994) It also has a library of pre-defined material properties for common types of surfaces with user control over reflectance, absorptance, transmittance and other properties. Radiance traces the paths of light backwards from the viewer to the light source in a "backwards ray tracing" method. Radiance can be used to model skylights in four ways[7]:

1. as a geometric model with the material properties of reflectance, absorptance and transmittance defined for each glazing layer of for the assembly of layers; or

[5] P. 2.50 F. Winkelmann et al, DOE-2 Supplement Version 2.1E, Lawrence Berkeley Laboratory, 1993.

[6] Window 5.1, Windows & Daylighting Group, Lawrence Berkeley National Laboratory.

[7] Personal communication Charles Erhlich, Heschong Mahone Group

2. as a virtual luminaire based upon the luminous intensity distribution as published in IES skylight photometric files from goniophotometric measurements;[8]
3. as a virtual luminaire generated from a geometric model of a skylight through the use of the mkillum program within Radiance.
4. as a combination of the above approaches where the virtual luminaire provides the general illumination of the space and the more complex geometric model is used to describe the appearance of surfaces (the underside of the skylight and the skylight well) that are behind the virtual luminaire

The first method requires the most computations and the most user inputs as it requires generating a physically accurate representation of the skylight and carefully defining the surface properties which sometimes includes a detailed bi-directional reflectance (or transmittance) function, BRDF, of the glazing material. Usually BRDF's are not available and the user must make an estimate of diffuse versus specular transmittance based upon the measured quantity haze. For some materials such as prismatic and light-redirecting surfaces the location of the solar disk must be known to provide an accurate simulation.

The second method is the least computationally intensive and does not require a detailed representation of geometry or material properties. However, this method does not provide a rendering of the geometric shape of the skylights and only approximates the light distribution in near field situations when the light is impinging on surfaces closer than 5 times the largest dimension of the skylight. Skylight photometric files derived from goniophotometric measurements were only recently created as part of this same PIER skylight testing program (McHugh et al. 2002). Photometric files from 7 different skylights on a variety of lightwells were published. It is our hope that this method will become widespread, but in the short term there are not many skylight photometric files available.

The third method while requiring the same detailed inputs of the first method is less computationally intensive than a combined Radiance calculation as the problem has been broken down into two pieces: 1) the transfer of light from the sky to the skylight and 2) the transfer of light to the skylight to the room. This is a welcome addition since this can substantially reduce the computational time needed. This path has the shortcoming of the first method in terms of the time needed to generate the skylight geometry and the little detailed glazing properties information available.

The fourth method is similar to the second method in that the source of the light is a virtual luminaire having a measured photometric distribution. What differs is that a geometric representation of the skylight is created – not as a source of

[8] Skylight photometric files resulting from PIER testing available from www.newbuildings.org or www.h-m-g.com

light but as part of the room surfaces, so that one can visualize the room geometry including the underside of the skylight. The approach avoids some of the computational overhead associated with a complex, lighting-accurate model of the skylight system. Computational savings for this approach depend upon the complexity of the skylight and result from having fewer rays traced from the room surfaces toward the origin of the light. This hybrid modeling approach also allows the simulation of skylight systems that are computationally intractable, such as light-redirecting and prismatic lenses, because pre-computed (as with a forward ray-tracing program) or lab-measured photometric distribution is used with the virtual luminaire to provide the general illumination for the space.

Radiosity Programs

Most of the electric lighting design software that visualizes spaces does so by solving a matrix of the radiosity (combined emitted and reflected light) of each surface in a modeled geometry. The radiosity matrix simultaneously solves the fraction of light exiting each surface that impinges on other surfaces through the use of form factors. These form factors (as known as in thermal radiation transfer theory as view factors) are calculated based upon the assumption that all surfaces are diffusely reflecting. As a result, radiosity programs are unable to model specular surfaces accurately and semi-specular surfaces are approximated as diffuse (matte). (Ashdown 2002)

Electric lighting design software if it has a daylighting module at all, will treat skylights as being either perfectly clear or perfectly diffusing and as flat. However, real diffusing skylights are not perfectly diffusing. This type of skylight model thus can only differentiate between diffusing skylights based upon published transmittance but not in terms of the distribution of light. One lighting program that we tested did not vary skylight transmittance with sun angle. As it turns out, this is a reasonable thing to do for dome skylights, which have relatively constant visible transmittance with respect to sun angle. But for flat skylights, the assumption of constant transmittance overestimates transmitted light at low sun angles.

If skylight photometric files are available in IESNA LM-63 format, the skylight can be modeled as an electric lighting luminaire. However, the sun position and the solar illuminance on the day the skylights are tested may vary from the conditions one wants to model for their project. The process of “tricking” the electric lighting design software to model daylighting with skylights by adjusting the “lamp lumens” and the “luminaire rotation angle” is described in McHugh et al. (2002).

As described above, only a few tested skylight photometrics exist outside of those created as part of the PIER Integrated Ceiling skylight testing research. Additional limitations of this method are:

- far field photometric measurements will only approximate the near field interactions with wall and well surfaces

- calculations are based upon the distribution of light expanding spherically under the skylight (inverse square law assumption), light that is collinear violates this assumption

Thus this method does not work well for situations where there are large skylights over fairly low ceilings. In addition, using skylight photometry for poorly diffusing skylights will not provide accurate results. However, this method is acceptable for modeling diffusing skylights, which are desirable in commercial skylighting due to lower glare and better distribution of light.

Description of the Study

Skylights come in a variety of shapes, with many different glazing types and are placed over a variety of light wells (heights and surface properties) and in some cases have a separate diffuser. Often the only transmittance data available is the visible transmittance of the glazing material. This study attempts to provide guidance on what information is needed to accurately predict the hourly visible transmittance of skylighting systems for daylighting commercial buildings. Since most commercial buildings have low slope (less than 1/12 pitch) roofs, the skylights are mounted horizontally.

Thus we will be comparing skylight transmittance according to these test methods:

- Visible transmittance testing of single layers of flat glazing samples and glazing assemblies tested on a laboratory apparatus (BYK Gardner Haze Gard Cat. #4725) according to ASTM D1003.
- Visible transmittance testing of the skylight glazing in the form of the skylight using sunlight as the light source based upon the test methods in ASTM E1084.
- Effective Visible Transmittance (EVT) of the skylight, its light well and diffuser (if any) by the use of a regular grid of illuminance meters placed at the bottom of the light well.
- Skylight (luminaire) efficiency calculated from goniophotometric measurements that are based upon the IESNA LM-41 standard for photometric testing of indoor fluorescent luminaires.

This comparison will help us to identify what level of testing is required to accurately predict visible transmittance of skylights. This comparison will also help validate calculation algorithms for the transmittance of skylights.

METHODOLOGY

DSET Laboratories Standard Visible Transmittance (T_{vis}) Test

This test was conducted to determine the light transmission of diffusive flat skylight materials, such as used by the NFRC. Test results from this test will be compared to the results from the standard light transmittance test for curved skylights (conducted by Tait Solar Laboratories).

Methodology

Visible transmittance and transmission haze measurements are performed on the specimens in accordance with ASTM D1003-00 *Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics*, Procedure A. The measurements are made using BYK Gardner Haze Gard Cat. #4725. The transmission haze values were determined by the ratio of the diffuse transmittance to the total transmittance for each specimen. See Figure 9 for a diagram of the visible transmittance test apparatus.

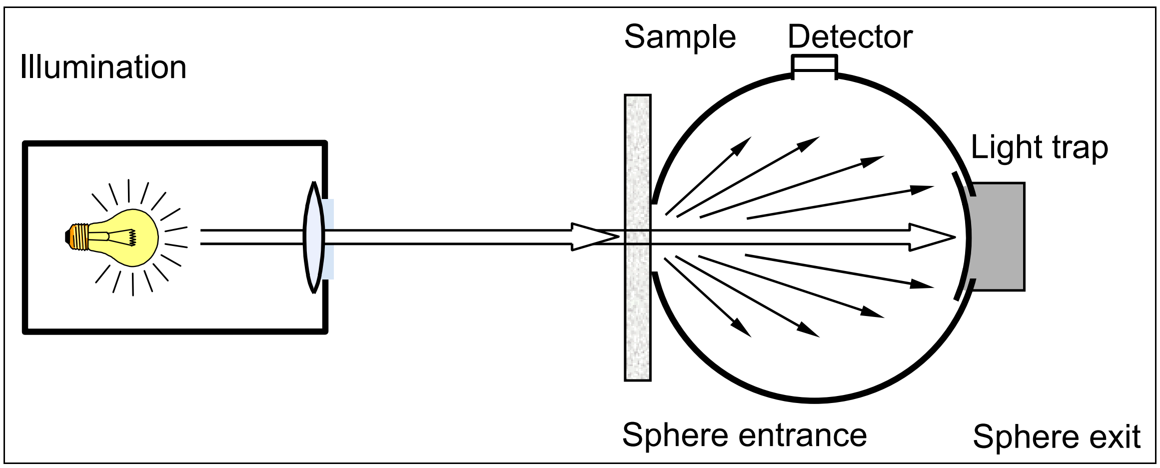


Figure Courtesy of BYK-Gardner

Figure 9. Measurement of Total Transmittance with Light Trap Covered

The Haze Gard consists of a light source, and integrating sphere with a light trap a light trap shield and three detectors. The light source matches the spectral distribution of CIE illuminant C. The light trap captures all light that is within a 2.5° acceptance angle of the beam of light emitted by the light source. If there is no glazing in place and the light trap is unshielded virtually all of the light is captured by the light trap. When there is no glazing in place and the light trap is shielded the integrating sphere detector shown on the top of Figure 9 measures the maximum amount of light reflected in the integrating sphere.

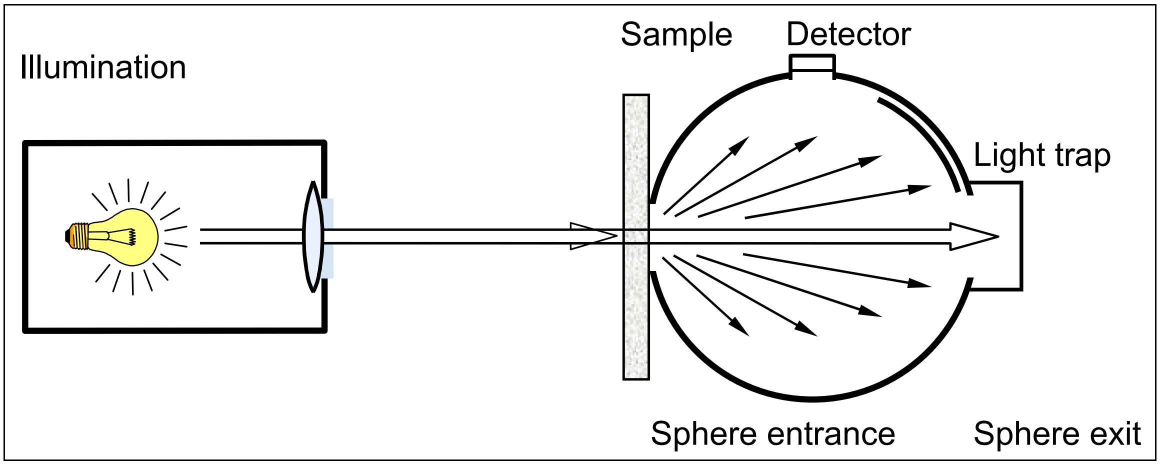


Figure Courtesy of BYK-Gardner

Figure 10: Measurement of Diffuse Transmittance with Light Trap Open

Total light transmitted by the glazing is measured with the light trap obstructed by a cover having the same reflectance as the rest of the integrating sphere (see Figure 9). Total transmittance is the ratio of the measured illuminance by the sphere detector with the glazing sample in front of the sphere aperture and the light trap covered, to measured illuminance by the sphere detector with the glazing sample removed and the light trap covered.

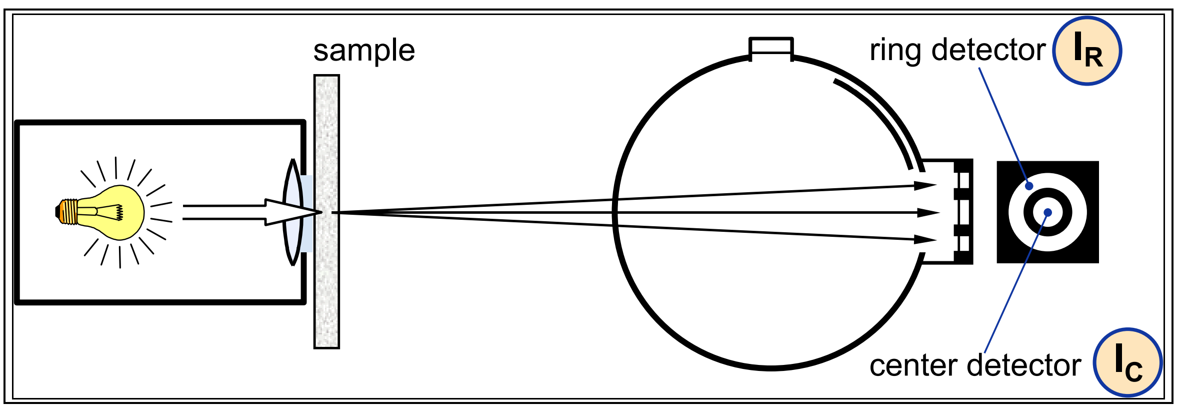


Figure Courtesy of BYK-Gardner

Figure 11: Center Sensor and Ring Sensor in Light Trap

Diffuse transmittance, $T_{Diffuse}$, is measured with the light trap uncovered as shown in Figure 10. In this configuration the sphere detector measures only the light not trapped – light which is scattered more 2.5°. Diffuse transmittance is used to quantify transmission haze, which is the wide-angle scattering of transmitted light through transparent and translucent materials. Haze is the ratio of diffuse transmittance to total transmittance and is expressed by the following relation:

$$\textbf{Haze} = \frac{T_{Diffuse}}{T_{Total}}$$

The center detector, as shown in Figure 11, is located in the center of the light trap and measures the amount of light that is transmitted without any scattering. The ring detector, in the shape of a ring that surrounds the center detector, measures the amount of light that is scattered within 2.5° of the center detector. These two sensors are used to measure clarity which is the relative intensity of light that is directly transmitted with no scattering to scattered light observed in a 2.5° acceptance angle. Clarity is defined in terms of the measured center detector intensity, I_C, and the ring detector intensity, I_R.

$$\textbf{Clarity} = \frac{\mathbf{I_C - I_R}}{\mathbf{I_C + I_R}}$$

Thus, a glazing sample that resulted in equal intensities of light being measured by the center detector (direct transmittance) and the ring detector (narrow angle scattering) would have a clarity of 0%. Conversely, if the light were sensed by the center detector and no light was sensed by the ring detector, the glazing clarity would be 100%. The clarity measurement by the Haze Gard instrument is not in accordance with any recognized test standard, but is of interest as it indicates the narrow angle light scattering caused by the glazing sample. Clarity measurement procedures are not part of the ASTMD1003 test standard.

Thickness measurements are taken as the average of four readings taken with a Starrett Digital Caliper No. 722.

The ASTM D1003 standard states that "material having a haze value greater than 30% is considered diffusing and should be tested in accordance with practice E167," *Standard Practice for Goniophotometry of Objects and Materials, American Society for Testing and Materials*. The problem with ASTM E166 (for transmitting materials) and E167 (for reflecting materials), is that this standard has no simple term for diffusing or non diffusing glazing. There is no concept of haze in ASTM E166, it merely defines the method of generating a photometric distribution. This result is not particularly useful in a code or a specification context where meting a given criteria is desired.

The concern with measuring haze from a highly diffusing sample is that it does cause some error but this error is small. In a paper by Weidner and Hsia (1979), the uncertainty in percentage haze is on the order of 0.2% of full scale for a highly diffusing (Lambertian) sample and as high as 2% if the haze samples have a concentrated directional scattering. As we will see later, 2% error is acceptable for the very gross distinctions in haze we are interested in.

Test Specimens

Ten specimens were tested in the 17 configurations tabulated in Table 3. The ten specimens were provided by the skylight manufacturers and are flat samples of the plastics used in the manufacture of skylights or well bottom diffusers. The samples were not formed but in the case of prismatic materials were already embossed with their prismatic pattern. The configurations were selected as match the configurations of glazing in the skylights.

In selecting these glazing types we had several criteria:

- Common commercial skylight glazings. White acrylic is perhaps the most popular glazing used. Most of the other glazing types are also commonly used.
- Different methods of diffusion. The white skylights scatter light by pigments, the fiberglass skylights scatter light by fibers, and the prismatic and structured polycarbonate skylights scatter light by refraction.

The interest in different methods of diffusion is due to the recognition that higher visible transmittance is desirable but so is good diffusion of light. When pigments are used to diffuse light, higher diffusion results in lower transmittance. In the past, focusing solely on transmittance had led to high transmittance, low diffusion white skylights. These skylights produced excessive contrast causing glare and because the light was not spread enough, resulted in *lower light levels between skylights* than lower transmitting but better diffusing medium white skylights.

Diffusing light via refraction or other methods offers the possibility of having both high visible transmittance and high diffusion. Some skylight manufacturers are combining diffusion methods e.g. creating prismatic or structured glazings with small amounts of pigment. For simplicity of analysis, this sample of glazing types does not contain products with combined diffusion methods.

Table 3. DSET Laboratories Test Specimens.

Tests	Material 1 (outside)	Material 2 (inside)	Description
1	White Acrylic	--	
2	Clear Acrylic	--	
3	Clear Acrylic	White Acrylic	Assembly with 1/16” air gap.
4	Clear Acrylic	White Acrylic	Same as above with 1” gap
5	Bronze Acrylic	--	
6	White PET	--	
7	Thicker prismatic	--	Prisms facing light
8	Thicker prismatic	--	Prisms away from light
9	Thinner prismatic	--	Prisms facing light
10	Thinner prismatic	--	Prisms away from light
11	Thicker prismatic	Thinner prismatic	Material 1 prisms facing away from light, 1/16” gap, Material 2 with prisms

Tests	Material 1 (outside)	Material 2 (inside)	Description
			facing light
12	Thicker prismatic	Thinner prismatic	Same as above with 1" gap
13	Twinwall polycarbonate	--	
14	Fiberglass assembly	--	Side with no fill (more transmitting)
15	Fiberglass sheet	--	Avoid scratch
16	Prismatic diffuser	--	Prisms facing light
17	Prismatic diffuser	--	Prisms away from light

In combining more than one glazing layer in a test, we are deviating from the ASTM D1003 test procedure. The test procedure is developed for single layers of glazing only. We wanted to know if we could get reasonable results by combining the layers and altering the spacing of the gap between layers.

We also wanted to compare the performance of prismatic glazings with the prisms pointed towards and away from the source of light. It was hypothesized that pointing the prismatic side towards the light source would increase visible transmittance as the prisms may act like light traps similar to those used to boost the output of photovoltaic cells. (Campbell & Green, 1987, Parretta et al. 2003)

When the twinwall polycarbonate glazing (test No. 13) was tested, it was measured twice – once with the "flutes" or tubes facing up and another with the tubes oriented horizontally – the results were then averaged. It was thought this may reduce any systematic error related to orientation.

Standard Visible Transmittance (T_{vis}) Test using Sunlight

Tait Solar conducted the Standard Visible transmittance tests on skylights outdoors using the sun as the light source. The purpose of measuring the standard visible transmittance values of the skylight products was to compare the difference in light transmittance performances of flat glazing samples (DSET Laboratories Standard Visible Transmittance Test) to the transmittance of glazing after it has been formed and installed in a skylight. Does the skylight glazing forming process or the different test procedure result in vastly different measured transmittances?

Methodology

The Standard Visible Transmittance Test was conducted according to ASTM E972-88 *Standard Test Method for Solar Photometric Transmittance of Sheet Materials Using Sunlight* and ASTM E1084 *Standard Test Method for Solar Transmittance (Terrestrial) of Sheet Materials Using Sunlight*. It should be noted that the standard calls for flat, single layered product samples. Therefore these test results cannot be officially referenced as "tested according to the ASTM E972-88 standard". There is no equivalent ASTM test standard for the complex skylight glazing systems tested.

ASTM E972-88 requires that visible transmittance be tested at direct-normal incident angle. The procedure requires measuring the illuminance values, with the sample in place, and then without the sample. This is referred to as the "full sun" value. The ratio of these two measurements determines the visible transmittance.

When the measurement is taken with the sample in place, the illuminance sensor is held 50mm (2") from the inner surface. According to an Advisory Group member, this method can result in a significant loss (as much as 15%) in transmissivity as compared to placing the sensor directly touching the inner surface.

The light meters used were LI-COR Model LI-210SA Photometric Sensors. These light sensors are cosine corrected up to 80° angle of incidence and have a sensitivity response function that is within 5% of the CIE Vλ photometric efficiency function.

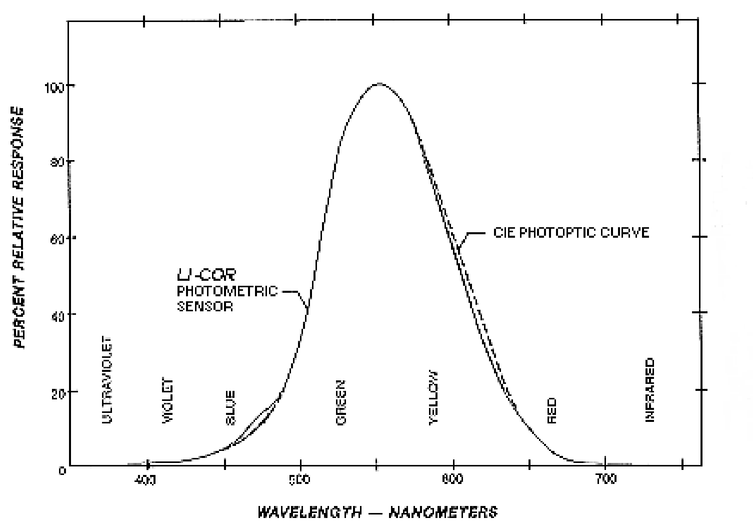
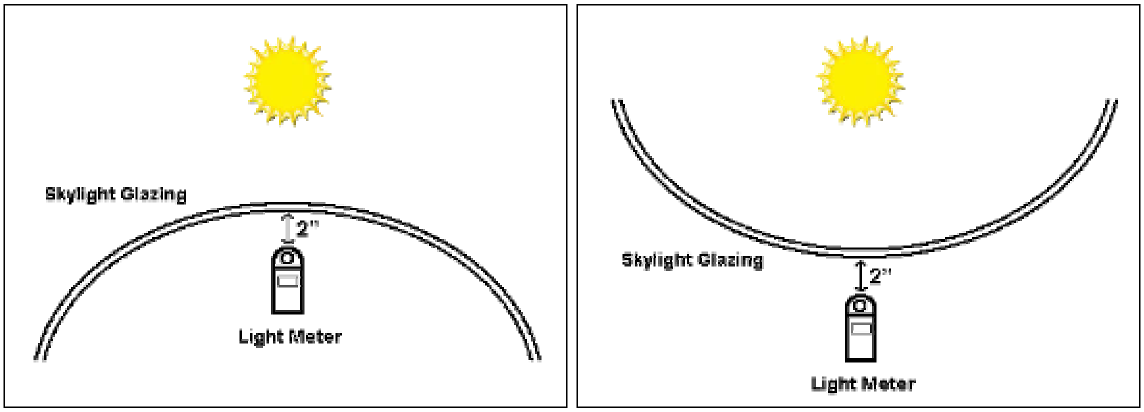


Figure 12. Spectral Response of LI-COR Photometric Sensor and the CIE Photometric Curve.

Both flat glass and curved glazing products were measured. For the skylight products that had curved glazing materials, the measurements were made from the inside and outside surfaces of the skylight to minimize possible errors from the concentration or spreading of the transmitted light due to the material curvature. Five measurements were made from both the concave (interior) side and five were made from the convex (exterior) side (see Figure 13). These ten readings were averaged. These five measurements were taken on relatively flat sections of glazing that were as close as possible to the four corners and the center of the skylight glazing to account for the varying thickness of the material around the curvature.



a) Concave / Interior Surface b) Convex / Exterior Surface.

Figure 13. Light Meter Position in Standard Visible Transmittance Test

Since the ASTM E 972-88 standard requires normal direct incident angle conditions, the skylight has to be rotated so that the section of the skylight glazing being measured is perpendicular to the rays of the sun (see Figure 14).

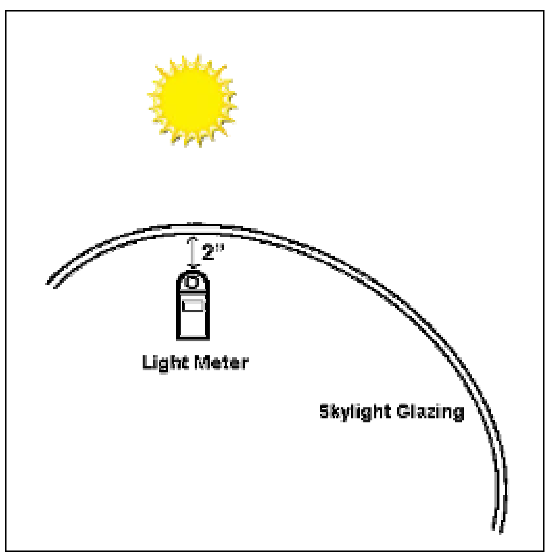


Figure 14. Diagram of TAIT Test with Light Normal-Incident on the Glazing.

Test Specimens

Table 4. lists the eight sample skylights tested. These are the same skylights that also were tested for Effective Visible Transmittance of the skylighting system including the skylight and light well. This sample of skylights includes a variety of commercial skylight shapes and glazing materials. For images of the test samples, refer to Figure 15 to Figure 21 below.

Table 4: Standard Visible Transmittance Test -- Description of Skylights

Type	Dimension	Material	Color	Shape
A	4' x 4'	Double-glazed Low-E glass	Clear	Flat - horizontal
B	31" x 39"	Double-glazed Low-E glass	Clear	Flat - 20° slope
C	4' x 4'	Single-glazed Acrylic	Medium-white (color 2447)	Dome
D	4' x 4'	Double-glazed Acrylic	Outer – clear Inner – medium white (color 2447)	Dome
E	4' x 4'	Double-glazed Prismatic Acrylic	Clear, with 12 prismatic pattern on the inside surfaces.	Catenary Arch Dome
F	4' x 4'	Fiberglass insulating panel, crystal over crystal glazing sheets with no fiberglass batt filling between sheets		Pyramid
G	4' x 4'	Structured Polycarbonate "Twinwall" Glazing	Clear	Pyramid
H	4' x 4'	Non-diffusing Acrylic Sheets	Bronze	Pyramid

Figure 15. Double-glazed Low-E Flat Skylight – Type A

Figure 16. Single-glazed White Acrylic Dome Skylight – Type C.

Figure 17. Double-glazed White Acrylic Dome Skylight – Type D.

Figure 18. Double-glazed Prismatic Acrylic Arch Skylight – Type E.

Figure 19. Fiberglass Pyramidal Skylight – Type F.

Figure 20. Twinwall Polycarbonate Pyramidal Skylight – Type G.

Figure 21. Bronze Acrylic Pyramidal Skylight – Type H.

Effective Visible Transmittance (EVT) Skylight Test

The effective visible transmittance, EVT, test describes the light transmittance of the skylighting system including the skylight, the light well and any diffusers that may be in the light well. Thus EVT testing accounts for the effects of skylight shape, skylight framing, well efficiency and diffuser transmittance. By testing skylights in installed configurations, it also gives results of varying solar conditions and typical skylight installations that reflect “real life” conditions. This provides information on how skylights tested in various rating protocols actually perform as installed in buildings.

Since we were interested in configurations typical for commercial buildings, we obtained commercial sized skylights and mounted them as they would be on the roof of a commercial building. In general unit skylights used on commercial buildings have at least 4 foot wide, thus we tested 4 foot by 4 foot skylights. Most commercial buildings have low slope roofs, thus we mounted the skylights horizontally. We also varied the light well height from 1 foot (no well) to 6 feet (a moderately deep well). Some commercial skylights have prismatic diffusers placed at the bottom of the light well so we tested diffusers in a couple of cases.

Methodology

We did not find any predefined test standard for measuring EVT. However the concept is relatively simple. The EVT is the ratio of the luminous flux exiting the bottom the light well to the ambient luminous flux impinging on the horizontal projection of the skylight rough opening.

The ambient luminous flux impinging on the horizontal projection of the skylight rough opening is the product of the ambient total horizontal radiation and the rough opening area of the skylight. The ambient luminous flux in lumens is given by:

$$\text{Ambient Luminous Flux} = E_{TH} \times A_{RO}$$

where,

E_{TH} = Total ambient (outdoor) horizontal illuminance, footcandles (lux)

A_{RO} = Horizontal projection of skylight rough opening, sf (m^2)

The luminous flux exiting the bottom the light well is the product of the average illuminance measured at the bottom of the light well and the area of the opening at the bottom of the light well. The exiting luminous flux in lumens is given by:

$$\text{Exiting Luminous Flux} = \frac{\sum_{i=1}^{N} EG_i}{N} \times A_{Grid}$$

where,

EGi = the illuminance at the ith sensor of the grid of sensors at the bottom the light well, footcandles (lux)

N = number of illuminance sensors that make up the illuminance grid at he bottom the light well

A_{Grid} = area of the bottom of the light well, sf (m^2)

Given the definitions of Exiting Luminous Flux and Ambient Luminous Flux, Effective Visible Transmittance is readily calculated as:

$$EVT = \frac{\text{Exiting Luminous Flux}}{\text{Ambient Luminous Flux}} = \frac{\frac{\sum_{i=1}^{N} EG_i}{N} \times A_{Grid}}{E_{TH} \times A_{RO}}$$

To measure EVT accurately, it is important that ambient total horizontal illuminance, E_{TH}, and average illuminance exiting the light well be measured simultaneously. Since there can be substantial gradients in the illuminance exiting the bottom of the light well, the greater the number of sensors in the grid of interior illuminance meters, the better.

Since diffusing glazings smooth the distribution of light to a wider range of angles, the spatial gradient of illuminance at the bottom of the light well will be diminished. Thus measurement error will be less for diffusing skylights as compared to clear (non-diffusing) skylights. Diffusers placed at the bottom of the light well will have less impact because the diffuser is 2” away from the sensor and cannot spread the light in such a small gap. Tall diffusely reflecting light wells will have better exiting luminous flux measurement accuracy than specularly lined light wells due to the light distribution smoothing effect of diffuse reflections.

Test Equipment

The EVT of different skylights and skylight well combinations were measured simultaneously with measurements of solar heat gain. A description of the solar gain measurements is the topic of another PIER report (McHugh, Saxena & Dee 2002). The main impact of measuring solar gains is that the grid of light sensors was placed at the bottom of the skylight well at the opening of the Skylight Solar Calorimeter. Figure 22 illustrates the position of the light sensor grid relative to the other components that comprised the Skylight Solar Calorimeter Test System (SSCTS).

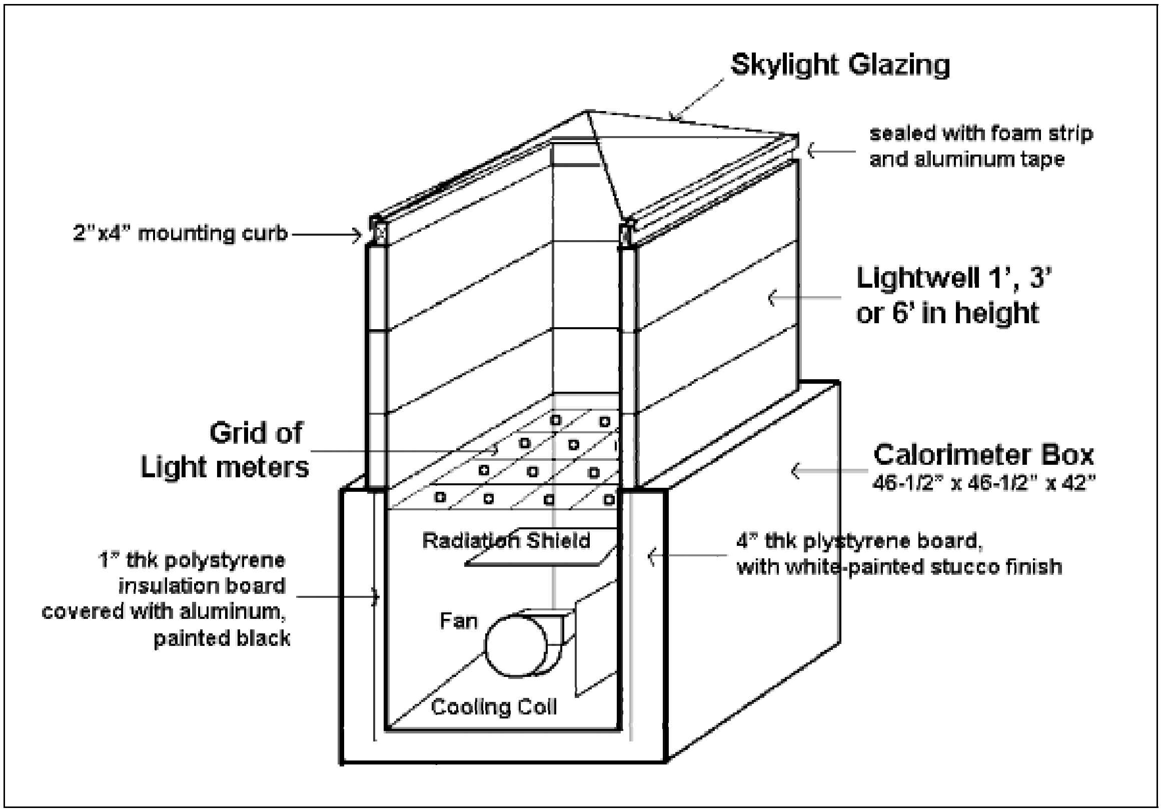


Figure 22. Cut-away isometric of the Skylight Solar Calorimeter Test System (SSCTS)

The calorimeter box is a heavily insulated test box with inside dimensions of 46-1/2" length by 46-1/2" width by 42" height. The inside box wall surfaces are made of 1" thick high-density polystyrene insulation board that has been covered with an aluminum sheet, and painted flat black for absorption. The bottom of the box has an additional ½" thick high-density polystyrene board. The outside box structure is made of 4" thick high-density polystyrene board finished with white-painted stucco for weather-protection. The 16 light sensors in the light well are held in place by an aluminum grid that kept the sensors evenly spaced. This light sensor grid was located above a radiation shield that was painted black – thus the grid of light sensors is above a black cavity.

The skylight samples were equipped with an attached 2"x4" mounting curb. The bottom edge of the skylight curbs had an adhesive-backed foam strip to prevent air and light leakage. The skylight samples were placed on the top of the skylight well and secured in place with mechanical fasteners to prevent movement.

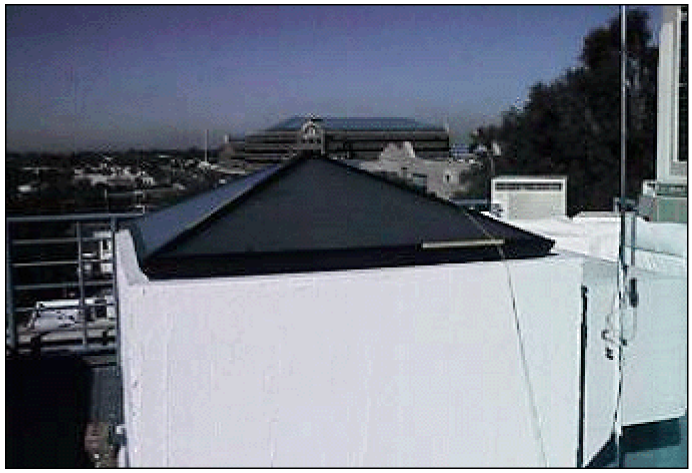


Figure 23. Photo of exterior of calorimeter box.

Sixteen light meters were mounted inside the calorimeter box, slightly below the ceiling diffuser level. The spacing of the interior light meters is shown in Figure 24.

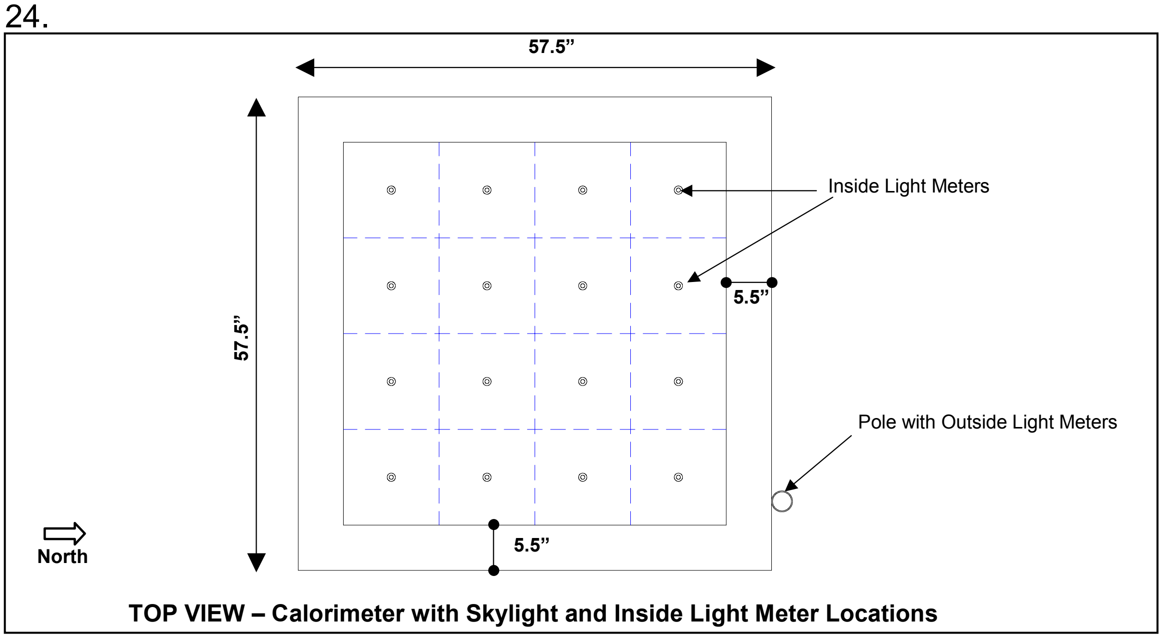
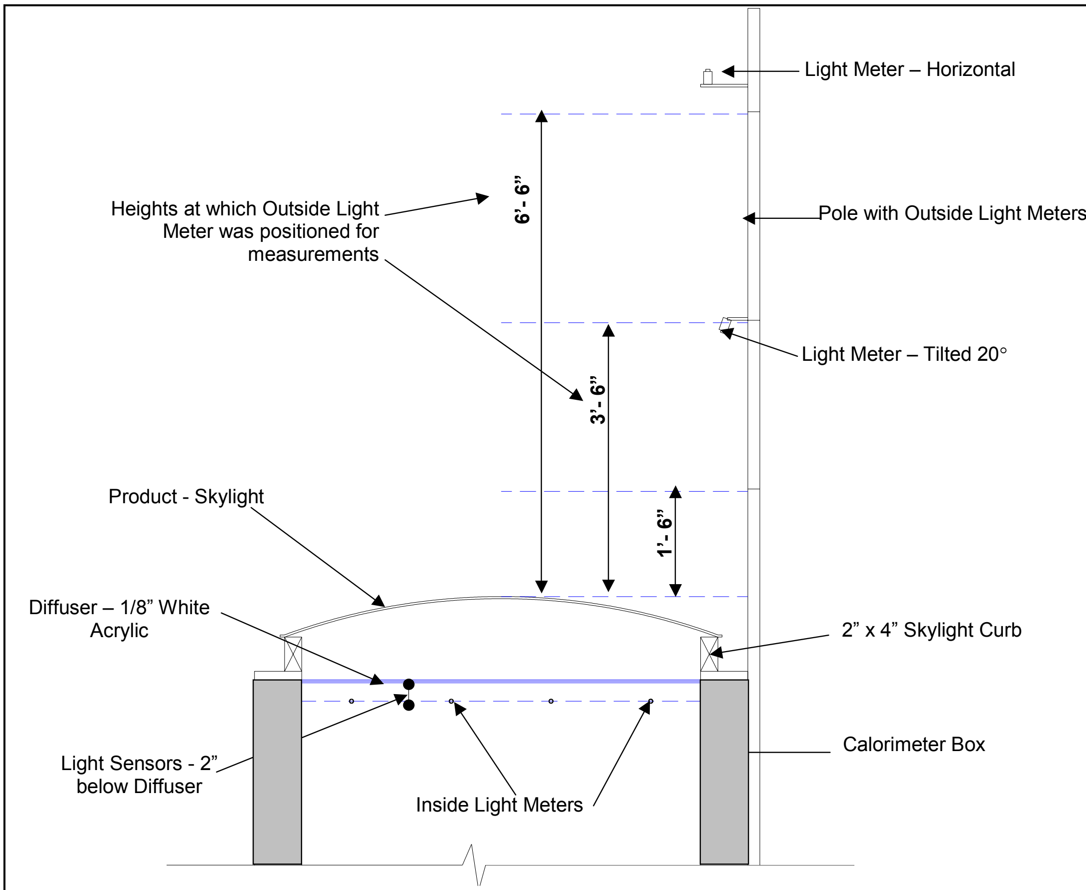


Figure 24. Grid of light meter installed in the calorimeter box (plan view).

Two additional light meters were mounted on the outside of the test system to take ambient illuminance measurements. One meter is measuring total horizontal illuminance and the other meter is measuring illuminance on a 20° tilted plane. The tilted light meter measures the light incident on the one flat skylight that has an adapter to impart a 20° tilt to the skylight. See Figure 25 for light meter configurations. As shown is that horizontal light meter height is maintained at a constant 6 inches above the top of the skylight.



Sectional Side View – Calorimeter with Skylight showing location of Inside and Outside Light Meters and Diffuser Location

Figure 25. Diagram of light meter installations in EVT skylight testing (side view).

The light meters used were Licor Model LI-210SA Photometric Sensors. As can be seen in Figure 12, the spectral response of these sensors is very close (within 5% under most light sources) to the spectral response of the eye as represented by the CIE photometric curve. This sensor is also cosine-corrected up to an 80° angle of incidence. The current signals from the sensors were converted into voltages as they passed through a precision resistor. These voltages were measured and recorded by a HP 34970A data acquisition system.

Test Specimens

Table 5 lists the descriptions of the 24 VLT tests that were conducted on the eight sample skylights. Twenty of the tests used a white diffusing inner surface on the skylight wells leaving four tests with a highly reflective inner skin on the skylight well surfaces. The conditions unique to each skylight test are the tilt, well height, well surface (reflective / specular or flat white), and whether a diffuser was installed at the bottom of the lightwell.

Table 5. TAIT Laboratories Standard Light Transmittance Test Configurations.

Test No.	Material	Well Height	Well Surface	Diffuser (yes or no)
1	Double-glazed Low-E glass - flat	3'	Diffuse	No
2	Double-glazed Low-E glass - tilt	3'	Diffuse	No
3	Double-glazed Low-E glass - flat	3'	Specular	No
4	Double-glazed Low-E glass - tilt	3'	Specular	No
5	Single-glazed White Acrylic Dome	1'	Diffuse	No
6	Single-glazed White Acrylic Dome	3'	Diffuse	No
7	Single-glazed White Acrylic Dome	6'	Diffuse	No
8	Double-glazed Acrylic Dome	1'	Diffuse	No
9	Double-glazed Acrylic Dome	3'	Diffuse	No
10	Double-glazed Acrylic Dome	6'	Diffuse	No
11	Single-glazed White Acrylic Dome	3'	Specular	No
12	Single-glazed White Acrylic Dome	6'	Specular	No
13	Single-glazed White Acrylic Dome	3'	Specular	Yes
14	Single-glazed White Acrylic Dome	6'	Specular	Yes
15	Double-glazed Prismatic Acrylic, Catenary Arch	1'	Diffuse	No
16	Double-glazed Prismatic Acrylic, Catenary Arch	3'	Diffuse	No
17	Double-glazed Prismatic Acrylic, Catenary Arch	6'	Diffuse	No
18	Fiberglass Panel - Pyramid	1'	Diffuse	No
19	Fiberglass Panel - Pyramid	3'	Diffuse	No
20	Fiberglass Panel - Pyramid	6'	Diffuse	No
21	Polycarbonate “Twinwall” Pyramid	1'	Diffuse	No
22	Polycarbonate “Twinwall” Pyramid	3'	Diffuse	No
23	Bronze Acrylic Sheets	3'	Diffuse	No
24	Bronze Acrylic Sheets	3'	Diffuse	Yes

Skylight Photometry Test

Photometric information, a description of the angular distribution of light from a source, is the basis of predicting how that light source will light a space. Photometric distributions describe the directionality and the magnitude of light from a given lighting source. Almost all electric light fixtures sold in the United States have a photometric report. This photometric information allows one to calculate how the light fixtures shall distribute light in a room. As part of this same PIER skylight testing program, Lighting Sciences Inc. conducted photometric tests on 22 skylight/light well combinations which resulted in photometric data files and reports for each of these combinations at various sun angles (McHugh 2003b). One metric generated by the photometric report is the “luminaire” efficiency which is equivalent to the effective visible transmittance of the skylight/light well system.

Methodology

The Illuminating Engineering Society of North America (IESNA) has documented the photometric test practices for most lighting devices in its Light Measurement (LM) series. However, there is no established test standard for measuring the photometric distributions from skylights. The essence of measuring photometric distributions is to measure the luminous flux (lumens) of the source and once stabilized to install this source in a luminaire. The luminous intensities (candela) that are emitted by the luminaire are measured at regular angular intervals on a goniophotometer. The goniophotometer as shown in Figure 26 has sensors that measure light at 10º vertical angle intervals and the goniophotometer is rotated in 22.5º increments to capture these measurements in a full hemisphere beneath the skylight opening. (McHugh 2003b)

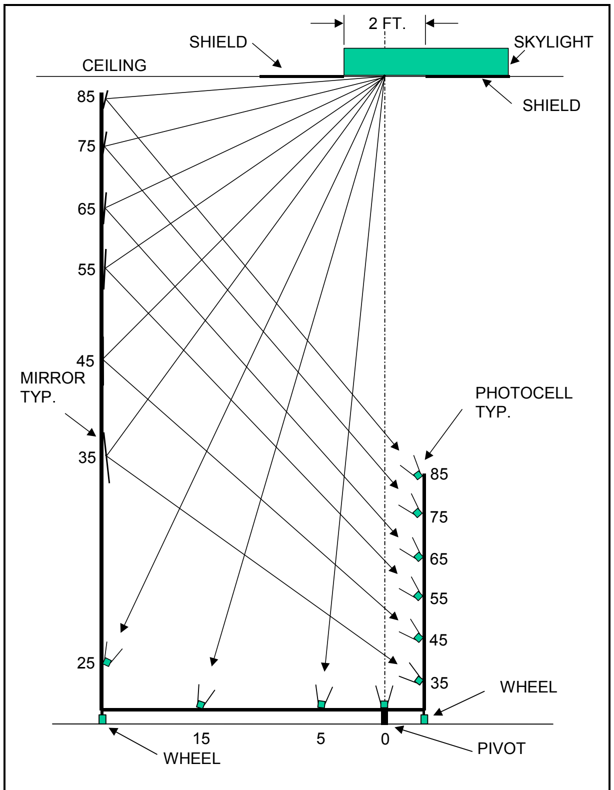


Figure 26: Skylight Goniophotometer

In general, the light output of the source is stabilized and well defined before the luminous intensities are measured from a luminaire. However, in this case the source, the sun, is constantly changing. Instead of measuring absolute values of luminous intensities for a source of a fixed luminous flux, the luminous intensities exiting the bottom of the skylight and the luminous flux impinging on the horizontal projection of the skylight surface are simultaneously measured. These luminous intensities are then normalized by the luminous flux so that the photometric distribution intensities are in units of candelas per 1,000 lumens impinging on the top of the skylight. (Domigan et al 2002)

Test Specimens

Similar to the other tests, the single glazed white acrylic skylight was combined with the most permutations of light well conditions. In iaddtion to measuring the total luminous flux beneath the skylight, the primary purpose of these tests were to document the effect skylight shape and light well configuration has on distribution of light from the skylighting system. Most of these specimens are the same as the skylights tested by Tait Solar for EVT except that this series of tests also includes a white PET compound parabolic arch skylight.

Table 6: Photometric Testing – Skylight Description and Well Conditions

Test No.	Skylight Description	Well and other description
1	Flat glass double low-e, double glazed, clear low-e glass	1 ft deep white light well
2	Flat glass double low-e, double glazed, clear low-e glass	3 ft deep white light well
3	Flat glass double low-e, double glazed, clear low-e glass	6 ft deep white light well
4	Flat glass double low-e, double glazed, clear low-e glass	6 ft deep white light well w/ bottom diffuser
5	Dome, single glazed, white acrylic glazing	1 ft deep white light well
6	Dome, single glazed, white acrylic glazing	3 ft deep white light well
7	Dome, single glazed, white acrylic glazing	6 ft deep white light well
8	Dome, single glazed, white acrylic glazing	3 ft deep silver light well
9	Dome, single glazed, white acrylic glazing	6 ft deep silver light well
10	Dome, single glazed, white acrylic glazing	3 ft deep silver light well with bottom diffuser
11	Dome, single glazed, white acrylic glazing	6 ft deep silver light well with bottom diffuser
12	Dome, double glazed, clear acrylic over white acrylic glazing	1 ft deep white light well
13	Compound parabolic, clear prismatic acrylic over clear prismatic acrylic glazing	Major axis perpendicular to ridges, 1 ft deep white light well
14	Compound parabolic, clear prismatic acrylic over clear prismatic acrylic glazing	Major axis perpendicular to ridges, 6 ft deep white light well
15	Compound parabolic, clear prismatic acrylic over clear prismatic acrylic glazing	Major axis perpendicular to ridges, 1 ft deep white light well
16	Pyramid, fiberglass insulating panel glazing with no fill	1 ft deep white light well
17	Pyramid, fiberglass insulating panel glazing with no fill	6 ft deep white light well
18	Pyramid, twinwall structured polycarbonate glazing	1 ft deep white light well
19	Pyramid, twinwall structured polycarbonate glazing	6 ft deep white light well
20	Pyramidal, single glazed, bronze acrylic glazing	3 ft deep white light well
21	Compound parabolic, single glazed, medium white PET glazing	Major axis perpendicular to ridges, 1 ft deep white light well
22	Compound parabolic, single glazed, medium white PET glazing	Major axis perpendicular to ridges, 1 ft deep white light well

RESULTS

DSET Laboratories Standard Visible Transmittance (T_{vis}) Test

As shown in Table 7, prismatic acrylic (except double-glazed prismatic with a 1" gap), clear acrylic and twinwall polycarbonate glazings have the highest transmittances, T_{vis}. The bronze acrylic skylight and the fiberglass assembly have the lowest transmittances.

Table 7. Results of DSET Laboratories' Standard Visible Transmittance Test.

Test	Materials	Thickness in Inches	% T_{vis}	% Haze	% Clarity
1	White Acrylic	0.118	62.6	100	18.7
2	Clear Acrylic	0.118	94.9	0.3	99.8
3	Clear Acrylic outside, White Acrylic inside – 1/16" gap	0.298	59.4	100	17.7
4	Clear Acrylic outside, White Acrylic inside – 1" gap	1.236	58.0	100	17.0
5	Bronze Acrylic	0.116	28.2	1.5	99.7
6	White PET	0.117	48.8	100	6.4
7	Thicker prismatic prisms facing light	0.225	95.3	96.7	57.2
8	Thicker prismatic prisms away from light	0.225	84.8	98.1	61.1
9	Thinner prismatic prisms facing light	0.117	96.6	97.2	13.9
10	Thinner prismatic prisms away from light	0.117	87.7	97.2	15.0
11	Thicker prismatic outside, thinner inside – 1/16" gap	0.404	80.0	99.7	7.5
12	Thicker prismatic outside, thinner inside – 1" gap	1.342	45.5	100	9.3
13	Twinwall polycarbonate	0.241	83.6	33.2	80.9
14	Fiberglass assembly	2.750	29.2	92.2	13.4
15	Fiberglass sheet	0.067	79.1	69.0	23.5
16	Prismatic diffuser prisms facing light	0.180	93.3	97.4	4.9
17	Prismatic diffuser prisms away from light	0.180	85.8	97.2	5.1

The materials that provide best wide-angle diffusion are those with high haze values and include prismatic glazing and diffusers, white acrylic, double-glazed acrylics, white PET, and fiberglass assembly. Those samples with the lowest measured haze are the clear acrylic and the bronze acrylic. Though not measured, the glass used in the skylights test would have extremely low haze values. Many of the materials that provide high levels of wide angle scattering, also provide high levels of narrow angle scattering as defined by clarity. The lower the clarity number, the greater the narrow angle scattering. Ideally a diffusing glazing provides both high levels of haze and low levels of clarity.

The following analysis were derived from the data:

- Prismatic lenses with prisms facing the light perform about 10% better than when the prisms face away from the light.
- Layered diffusing materials have a higher tested visible transmittance when the gap between layers is smaller. This is an artifact of the test method and not an actual reduction in the amount of light transmitted. The reasons for this are discussed later in this section.
- Though they are a commonly used skylight glazing material, pigmented white acrylic materials perform satisfactorily, with a T_{vis}. around 60%.

Table 8. Ranking of test specimens according to haze rating.

Test	Material	Specimen Code	% Haze
1	White Acrylic	A	100
3	Clear and White Acrylic 1/16" gap	A + B	100
4	Clear and White Acrylic 1" gap	A + B	100
6	White PET	D	100
12	Thinner and Thicker prismatic 1" gap	E + F	100
11	Thinner and Thicker prismatic 1/16" gap	E + F	99.7
8	Thicker prismatic prism away fr light	E	98.1
16	Prismatic diffuser prism facing light	J	97.4
9	Thinner prismatic prism facing light	F	97.2
10	Thinner prismatic prism away from light	F	97.2
17	Prismatic diffuser prism away from light	J	97.2
7	Thicker prismatic prism facing light	E	96.7
14	Fiberglass assembly	H	92.2
15	Fiberglass sheet	I	69
13	Twinwall polycarbonate	G	33.2
5	Bronze Acrylic	C	1.5
2	Clear Acrylic	B	0.3

As can be seen in Table 8, there is a very obvious demarcation in haze ratings of existing skylight materials. Most of the test specimens are rather either above 92% or 70% and lower. The haze properties of less diffusive materials fall rapidly beyond 70%. Thus the concern expressed about the 2% error generated by measuring the haze of highly diffusing glazings is not important when making a clear separation between diffusing and non-diffusing glazings.

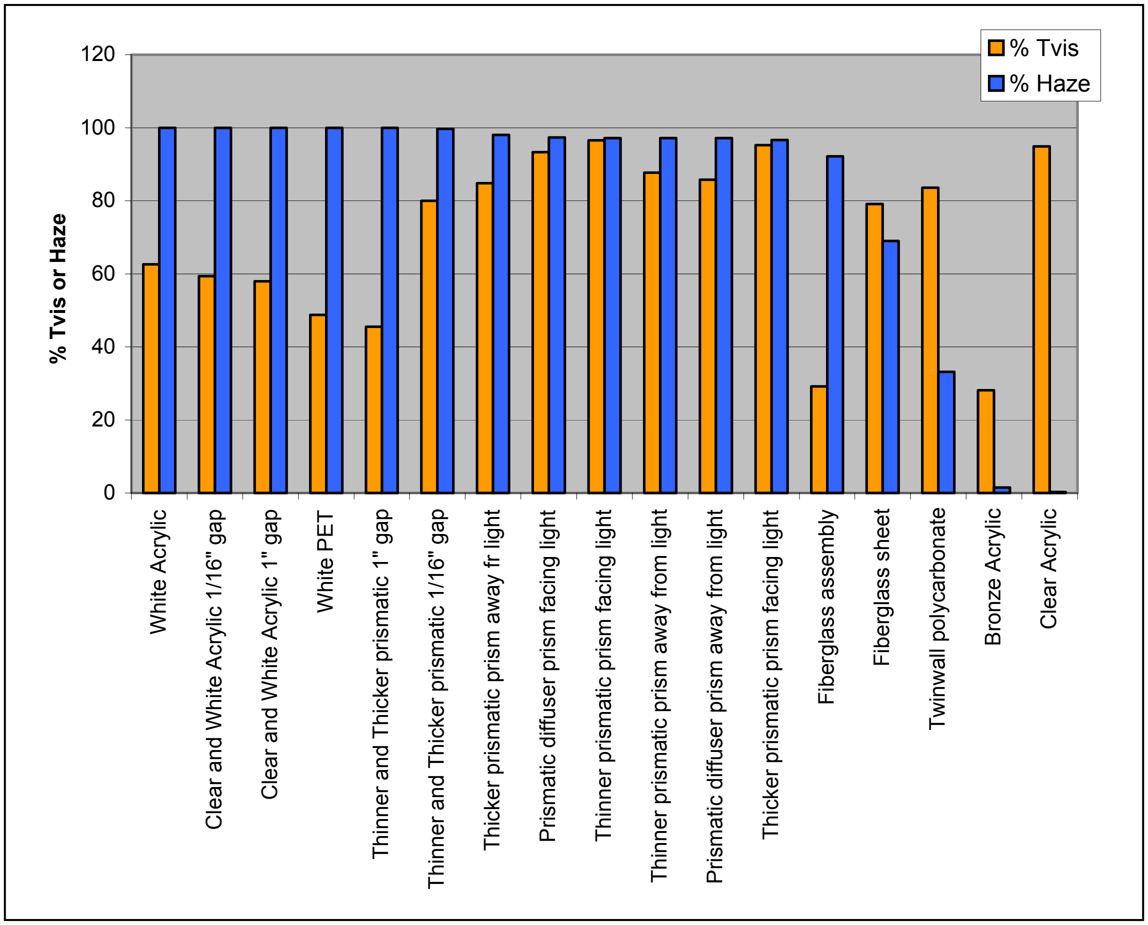


Figure 27. T_{vis} and Haze Rating of Test Specimens.

Figure 27 shows that materials in the mid-section of the chart have good light transmittance and diffusion properties. Single- and double-glazed prismatic skylights provide good light quality in both metrics, with the exception of double-glazed prismatic skylights with a 1" gap between layers.

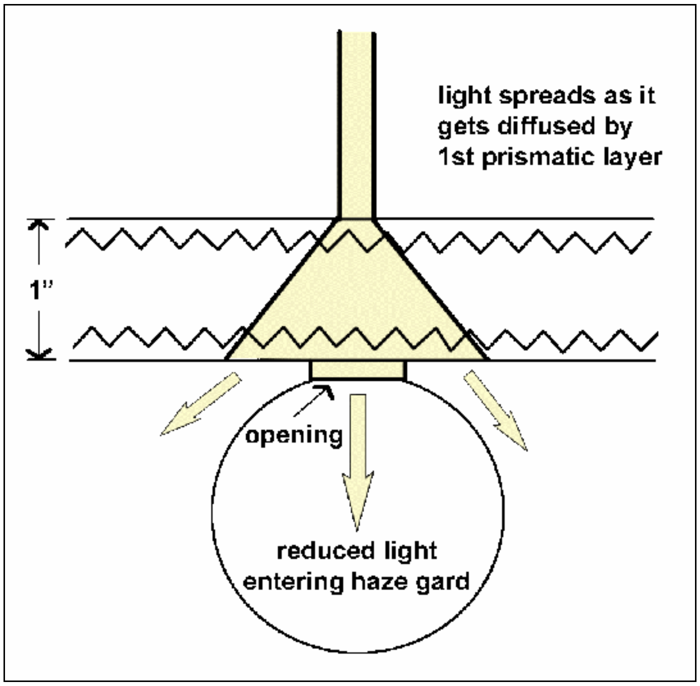


Figure 28. Light Transmission of Double-Glazed Prismatic Glazing (1" Gap).

The test method for T_{vis} measurement might have accounted for the low visible transmittance of this material. With a prismatic 1st layer, the 1" gap allows for substantial light diffusion to occur before light is transmitted onto the 2nd prismatic layer for light measurement (see Figure 28). With a small opening in the Haze-Gard, only a small amount of light actually gets transmitted into the measuring equipment while the rest is lost. In real installed conditions, all the light will be transmitted into the light well. Thus if one wishes to test the visible transmittance of multiple layers, one must minimize the gap between layers.

Standard Visible Transmittance (Tvis) Test

The results of the standard transmittance test are contained in Table 9. To determine whether it is important to measure both front side and backside transmittance, we have included the transmittance measured from the interior of the skylight, T_{vis} interior, and the average of the transmittances of tested from the inside and the outside, T_{vis} average. The difference in values of the T_{vis} interior and T_{vis} average is minimal, with a maximum of 4.2% difference

Using this test method, we achieved results similar to the results using ASTM D1003, bronze skylights have the worst light transmittance levels, while prismatic skylights have the best performance.

Skylight B, the double Low-E glass skylight tested at a 20° slope has a higher transmittance than the larger horizontally mounted skylight. The larger glass skylight, skylight A, has a lower transmittance due to a plastic interlayer added for more strength.

Table 9. Results of Standard Visible Transmittance Test.

Skylight Code	Dim	Material	Color	Shape	Tvis interior	Tvis average
A	4' x 4'	Double-glazed Low-E glass	Clear	Flat - horizontal	0.467	0.459
B	31" x 39"	Double-glazed Low-E glass	Clear	Flat - 20 deg slope	--	0.583
C	4' x 4'	Single-glazed Acrylic	Medium-white (color 2447)	Dome	0.542	0.531
D	4' x 4'	Double-glazed Acrylic	Outer – clear Inner – medium white (color 2447)	Dome	0.505	0.474
E	4' x 4'	Double-glazed Prismatic Acrylic	Clear, with prismatic pattern 12 on the inside surfaces.	Catenary Arch Dome	0.671	0.713
F	4' x 4'	Fiberglass insulating panel	crystal over crystal fiberglass glazing, without batt filling	Pyramid	0.443	0.474
G	4' x 4'	Structured Polycarbonate "Twinwall" Glazing	Clear	Pyramid	0.634	0.667
H	4' x 4'	Non-diffusing Acrylic Sheets	Bronze	Pyramid	0.254	0.239

Effective Visible Transmittance (EVT) Skylight Test

Though Tait Solar tested the EVT of skylights over the course of a day, the EVT summary in Table 10, is for a solar elevation of 30 degrees. This angle was selected for two reasons:

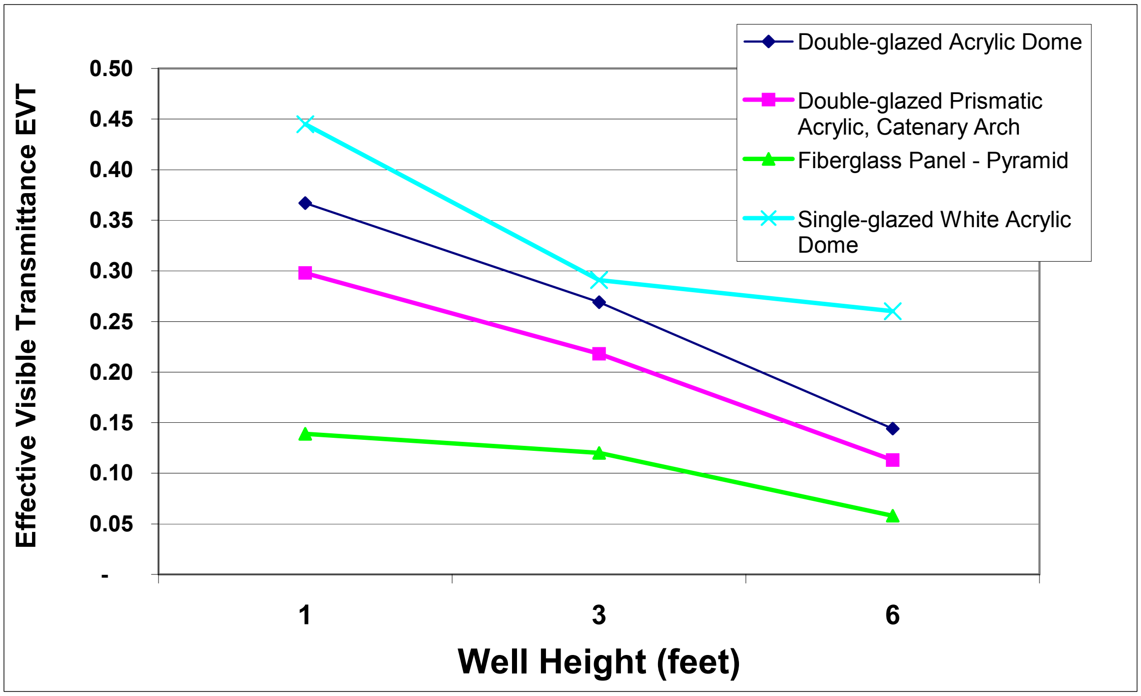
1. It was desired to compare skylights at he same solar elevations as the EVT changes with respect to sun angle. The skylight/well configurations were tested at different times of year and data for 30° was available for all the tests.
2. As shown in Figure 7 "Frequency of solar altitudes in San Diego, CA and Eureka, CA." The most frequent solar elevation is around 30°. Thus the EVT at a sun elevation of 30º is more representative of annual skylight performance than measurements taken at higher or lower elevations.

Table 10. Results of Calorimeter Box EVT Test at 30° Solar Elevation.

Test No.	Material	Well Height	Well Surface	Diffuser (yes or no)	EVT
1	Double-glazed Low-E glass - flat	3'	Diffuse	No	0.151
2	Double-glazed Low-E glass - tilt	3'	Diffuse	No	0.056
3	Double-glazed Low-E glass - flat	3'	Specular	No	0.253
4	Double-glazed Low-E glass - tilt	3'	Specular	No	0.111
5	Single-glazed White Acrylic Dome	1'	Diffuse	No	0.445
6	Single-glazed White Acrylic Dome	3'	Diffuse	No	0.291
7	Single-glazed White Acrylic Dome	6'	Diffuse	No	0.26
8	Double-glazed Acrylic Dome	1'	Diffuse	No	0.367
9	Double-glazed Acrylic Dome	3'	Diffuse	No	0.269
10	Double-glazed Acrylic Dome	6'	Diffuse	No	0.144
11	Single-glazed White Acrylic Dome	3'	Specular	No	0.462
12	Single-glazed White Acrylic Dome	6'	Specular	No	0.409
13	Single-glazed White Acrylic Dome	3'	Specular	Yes	0.354
14	Single-glazed White Acrylic Dome	6'	Specular	Yes	0.31
15	Double-glazed Prismatic Acrylic, Catenary Arch	1'	Diffuse	No	0.298
16	Double-glazed Prismatic Acrylic, Catenary Arch	3'	Diffuse	No	0.218
17	Double-glazed Prismatic Acrylic, Catenary Arch	6'	Diffuse	No	0.113
18	Fiberglass Panel - Pyramid	1'	Diffuse	No	0.139
19	Fiberglass Panel - Pyramid	3'	Diffuse	No	0.12
20	Fiberglass Panel - Pyramid	6'	Diffuse	No	0.058
21	Polycarbonate "Twinwall" Pyramid	1'	Diffuse	No	0.311
22	Polycarbonate "Twinwall" Pyramid	3'	Diffuse	No	0.193
23	Bronze Acrylic Sheets	3'	Diffuse	No	0.079
24	Bronze Acrylic Sheets	3'	Diffuse	Yes	0.061

An analysis of the test results above can be summarized as follows:

With constant light well width, EVT is reduced by 1% to 8% per feet of light well increase (See



- Figure 29).
- With the same skylight unit and light well depths, specular light wells are more efficient than diffusive light wells at directing daylight into the space. Measured EVTs of systems with specular light wells are 57% greater than those with diffusive light wells.
- Predictably, diffusers decrease the EVTs of skylight systems. In the systems tested above, there was an EVT decrease of 23%.

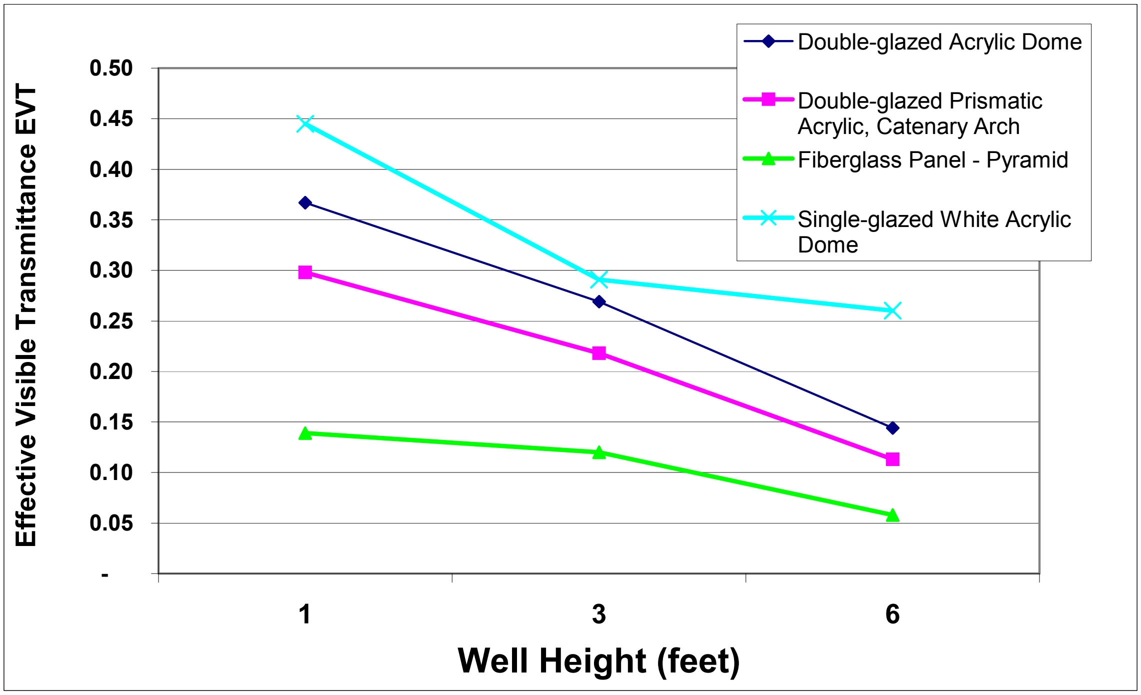


Figure 29. EVT as a Function of Well Height.

As mentioned in the introductory section of the report, existing test protocols assume that skylights are flat glass, without consideration for varying solar angles. The results in Figure 30 and Table 11 show that there is considerable difference in performance due to sun angles. This is perhaps the most important finding is this report.

The EVT for Test 1, a flat horizontal glass similar to existing protocols' assumptions, show results that are very similar to simulated skylight performance. When the skylight is horizontal as it was for these tests, the incident angle to the glazing is simply the zenith angle. In contrast, the visible transmittance for the dome skylights is relatively constant with respect to solar elevation

Table 11. Results of TAIT EVT tests varying according to solar angles.

EVT By 10 Degree Solar Altitude Angles										
Sample Test No.	**Solar Altitude Angle ***									
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
1		0.116	0.116	0.151	0.190	0.263	0.355			
2		0.048	0.042	0.056	0.074	0.086	0.153			
3		0.144	0.191	0.253	0.460	0.535				
4		0.077	0.074	0.111	0.153	0.203	0.280			
5		0.529	0.479	0.445	0.431	0.430	0.432			
6		0.437	0.327	0.291	0.281	0.282	0.290			
7		0.505	0.299	0.260	0.244	0.224				
8		0.394	0.385	0.367	0.372	0.388	0.408	0.426		
9		0.343	0.288	0.269	0.258	0.275	0.284			
10		0.175	0.151	0.144	0.147	0.155				
11		0.582	0.494	0.462	0.457	0.459				
12		0.545	0.445	0.409	0.402	0.390				
13		0.442	0.377	0.354	0.351	0.354				
14		0.412	0.337	0.310	0.308	0.314				
15		0.456	0.312	0.298	0.341	0.414	0.508	0.636		
16		0.257	0.214	0.218	0.241	0.301	0.381			
17		0.129	0.111	0.113	0.132	0.175				
18		0.127	0.120	0.139	0.176					
19		0.161	0.122	0.120	0.128	0.146	0.174			
20		0.059	0.054	0.058	0.066	0.077				
21		0.330	0.298	0.311	0.384	0.469	0.619			
22		0.223	0.186	0.193	0.223	0.257	0.376			
23		0.078	0.070	0.079	0.092	0.128	0.149			
24		0.056	0.053	0.061	0.069	0.091				

Projecting skylights have shapes that are not flat, and thus, there is no single angle of incidence for any sun angle. The angle of incidence of beam sunlight for any solar elevation changes with respect to location on the surface of the skylight. Thus calculations models that attempt to base projecting skylight transmittance on glazing transmittance are necessarily complex because of the changing incident angles with respect to position on the skylight. Laouadi & Atif (2001) have done just this and have calculated EVTs as shown in Figure 31, that were greater than 100% for dome skylights at low incidence angles. The results for our set of skylights were not that extreme but we did find that the EVT of projecting skylights was dramatically different from flat skylights and approached the shape that Laoudi and Atif have calculated. This is an important finding since the work of Laoudi and Atif is the basis of the dome skylight model in the skylighting software SkyVision.

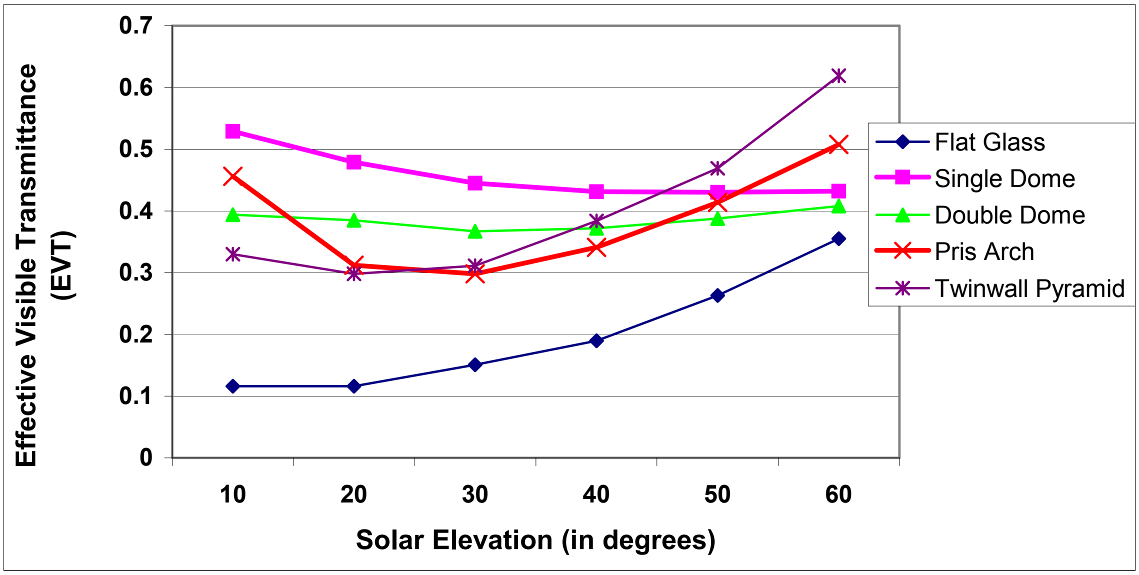


Figure 30. Performance of various skylights over varying sun angles.

When the sun is at a lower elevation, ambient daylight illuminance is also lower. Thus higher visible transmittances are needed at low solar elevations and lower visible transmittances are desirable at high solar elevations when there is an overabundance of daylight illuminance.

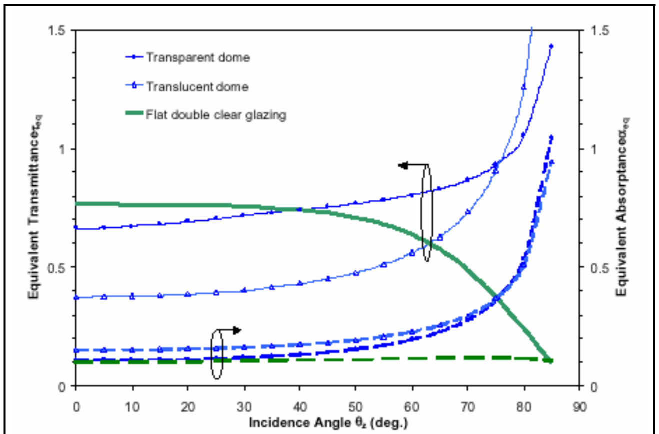


Figure 31: Dome Skylight Equivalent Transmittance (Laouadi & Atif 2001)

By graphing the EVTs of different skylight glazings at varying sun angles, we can determine the best glazing solution for skylights (see Figure 30).

- Dome skylights had higher EVTs at low sun elevations than at moderate of high sun elevations.
- Arch or compound parabolic skylights and pyramidal skylights had higher EVT's at low and high sun elevations than at moderate solar elevations.
- Glass and twinwall polycarbonate skylights have lower transmittance at low sun angles and higher transmittance at high sun angles.

ANALYSIS

Comparison of Test Methods

We wanted to know if there was any particular benefit to the various test methods and if they do provide mutual verification. For instance, if one plans to perform goniophotometric measurements to develop photometric files, when is there a need to take a separate measurement of effective visible transmittance.

Flat Sample Testing (DSET) vs. Curved Sample Manual Testing

For all test materials, the measured T_{vis} of flat samples consistently showed higher values than samples of complex shapes. This may be due to a systematic error in the calibration of the measurement equipment for either test. The notable exception to this rule is the Haze Gard measurements on the fiberglass insulating panel. The effect of multiple glazing layers spreading the light away from the integrating sphere opening and how it reduces the measurement of visible transmittance is illustrated in Figure 28 and described in the accompanying text.

For most of the test samples, T_{vis} measured from the interior resembles the DSET test results more closely than T_{vis} average.

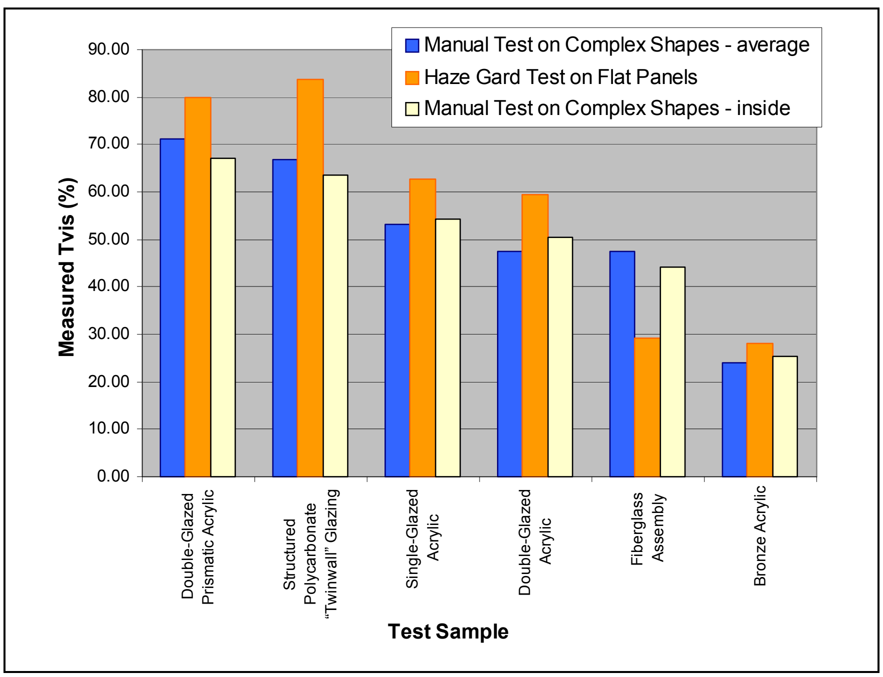


Figure 32. Comparison of T_{vis} of Flat Samples and Curved Samples.

Calculated T_{vis} of Flat Glass vs. Window 5.0 model

This analysis allows us to determine whether the test methods we used in this research yield results similar to the Window 5.0 software's calculated results. Since Window 5.0 assumes flat glass models, we compare its calculated results to the measured data for the double-glazed flat glass samples.

The first T_{vis} value is calculated from the EVT for varying solar angles as measured using ASTM E972. The second Tvis value is calculated from the EVT for varying solar angles as measured using photometric testing.

The general trend of T_{vis} is that it is increasing as the solar elevation increases, and this is consistent for all three measures. The difference among the different methodologies is the shape of the curve. Window 5.0 and T_{vis} from photometric testing show similar trends, except that Window 5.0 values flatten out as the sun gets higher overhead. T_{vis} from ASTM E972 testing shows the reverse pattern, with flatter T_{vis} at lower sun angles.

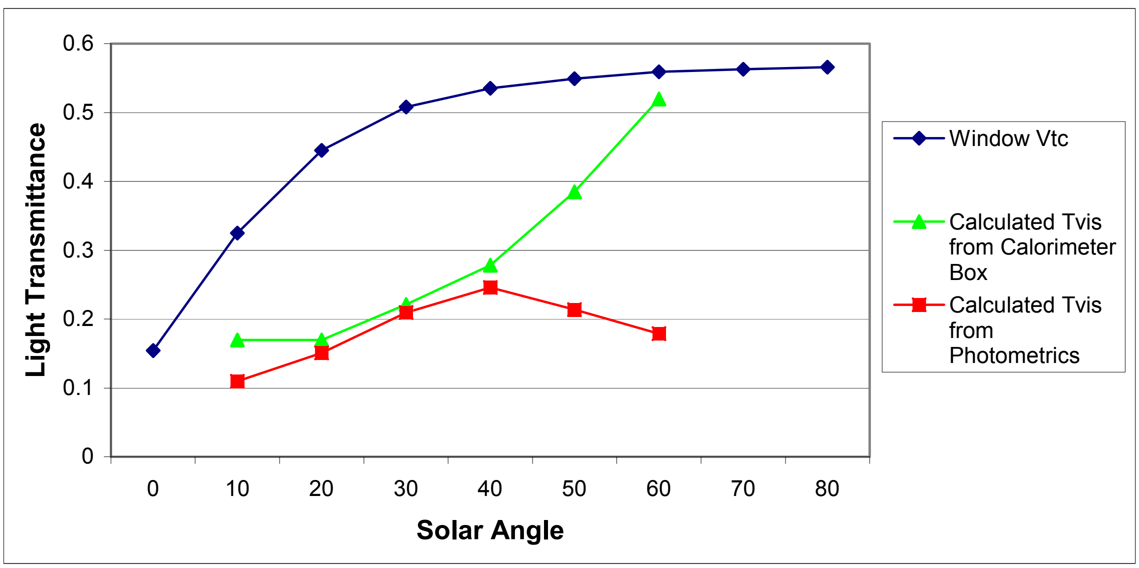


Figure 33. Comparison of T_{vis} over varying solar angles - Window software vs. Calculations from Calorimeter Box and Photometric Testing.

EVT from Calorimeter Box vs. Photometric Efficiency

Both the EVT measured via a grid of photometers and the skylight efficiency measured by the goniometric test refer to the same physical effect which is the fraction of light that impinges on the horizontal projection of the skylight opening that makes it through the bottom of the light well. In both tests, the amount of light (lumens) that impinges on the horizontal projection of the skylight opening is measured the same way: horizontal illuminance (foot-candles) is measured and multiplied by the horizontal projection of the skylight opening (square feet).

The two tests differ in how they measure the light (luminous flux in lumens) exiting the bottom of the light well. The EVT test measures the illuminance at the opening at the bottom of the light well by a grid of 16 illuminance meters. Each illuminance meter is representative of one square foot of light well opening. By multiplying the foot-candles of each illuminance meter by their representative area and summing this up across all 16 meters, yields the overall luminous flux (lumens) that leaves the bottom of the light well.

The goniophotometer sweeps an array of photometers mounted at different vertical angles azimuthally underneath the skylight. Measurements of luminous intensity (candela) are taken at regular intervals in positions that describe a hemisphere centered at the light well opening. Each measurement of luminous intensity has a solid angle (steradians) to which it corresponds. Multiplying the luminous intensity measurements by their corresponding solid angles yields the luminous flux (lumens) for a patch on the goniometric hemisphere that corresponds to the measurement taken at a given vertical and horizontal angle. Summing all of the luminous fluxes (lumens) on the hemisphere yields the total light in lumens leaving the bottom of the light well.

An evaluation of Calorimeter Box EVT values shows more consistent performance over varying solar elevations than do photometric efficiency values which tend to fluctuate more. See the Appendix for individual comparison graphs.

Table 12. Comparison of Visible Transmittance Values Using Calorimeter Box and Photometrics Testing at 30° Solar Angle.

Ref No.	Material	Well Height	Well Surface	Diffuser (yes or no)	Calorimeter Box EVT	Photometric Efficiency
11	Single-glazed White Acrylic Dome	3'	Specular	No	0.462	0.362
5	Single-glazed White Acrylic Dome	1'	Diffuse	No	0.445	0.464
12	Single-glazed White Acrylic Dome	6'	Specular	No	0.409	0.345
13	Single-glazed White Acrylic Dome	3'	Specular	Yes	0.354	0.493
21	Polycarbonate "Twinwall" Pyramid	1'	Diffuse	No	0.311	0.239
14	Single-glazed White Acrylic Dome	6'	Specular	Yes	0.310	0.427
15	Double-glazed Prismatic Acrylic, Arch	1'	Diffuse	No	0.298	0.437
15r	Double-glazed Prismatic Acrylic, Arch Rotated	1'	Diffuse	No	0.291	0.379
6	Single-glazed White Acrylic Dome	3'	Diffuse	No	0.291	0.289
7	Single-glazed White Acrylic Dome	6'	Diffuse	No	0.260	0.160
1	Double-glazed Low-E glass - flat	3'	Diffuse	No	0.151	0.143
18	Fiberglass Panel - Pyramid	1'	Diffuse	No	0.139	0.178
17	Double-glazed Prismatic Acrylic, Catenary Arch	6'	Diffuse	No	0.113	0.462
23	Bronze Acrylic Sheets	3'	Diffuse	No	0.079	0.069
20	Fiberglass Panel - Pyramid	6'	Diffuse	No	0.058	0.085

It should be noted that though the solar elevation was the same for each of these comparisons, the measurement of photometric efficiency and calorimeter EVT were not taken on the same day. Thus the azimuthal location of the sun will be different for the calorimeter EVT and photometric efficiency tests. In general, there is a good match between calorimeter EVT and photometric efficiency. Only test 17 (double glazed prismatic arch) shows a marked difference, this is likely due to testing error and should be considered an outlier. However the other tests on the prismatic skylight (tests15 and 15r) result in a fairly large deviation between the results from the two test methods. The transmittance of the prismatic arch may have more sensitivity to sun position than other shapes. Alternatively the refracted light from the prismatic glazing is somewhat collimated and thus this violates a key assumption of the photometric test method that the object measured is a source that has light expanding spherically from its center. If this is indeed the issue, this would imply that the calorimeter EVT method is a more robust method of measuring system overall transmittance as it is less impacted by the distribution of light exiting the light well.

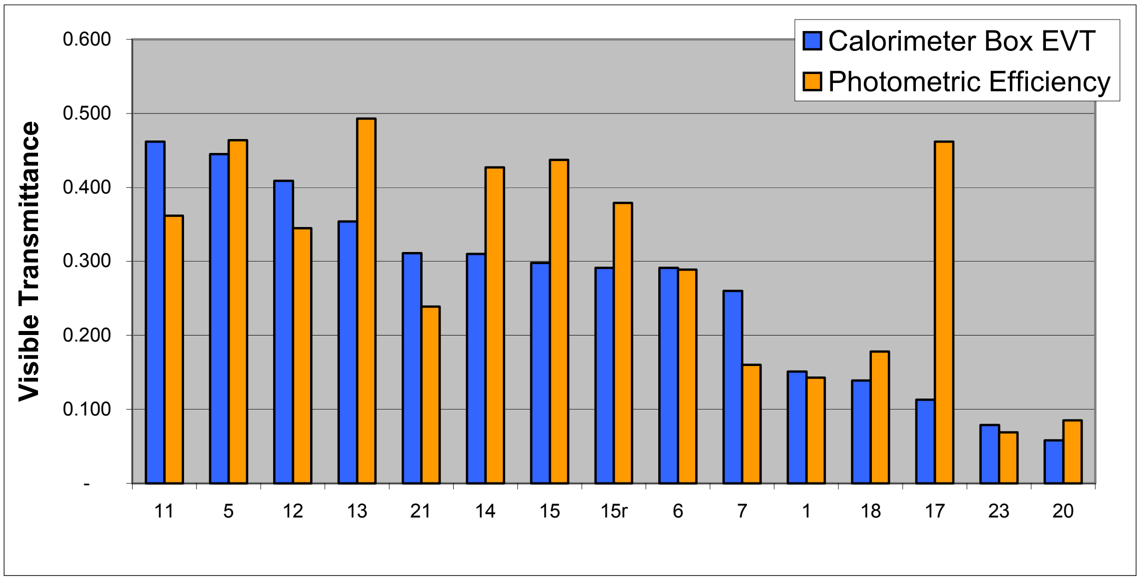


Figure 34. Comparison of Visible Transmittance Values Using Calorimeter Box and Photometrics Testing at 30° Solar Angle.

Relationship between Visible Transmittance of Glazing and EVT

One would expect that the visible transmittance of glazing would correlate well with the EVT of a skylighting system. In general this is true but as illustrated earlier in Figure 30, the shape of skylights has a significant effect on their EVT. Table 13 tabulates the measured glazing visible transmittance and the effective visible transmittance (EVT) of the same skylight over a 3 foot light well with white diffusing surfaces. As described earlier the EVT was measured at a solar elevation of 30º as this sun angle is near the median and mode of solar elevations over the course of the year in the lower 48 United States.

The data in Table 13 has been sorted by EVT in descending order from highest EVT to lowest. Though the single glazed acrylic dome had the third highest glazing visible light transmittance, its shape is more efficient at capturing light than other and thus it has the highest EVT. Though the dome's visible transmittance is only 16% greater than that of the flat glass skylight, its effective visible transmittance at a 30 solar elevation is almost twice that of the glass skylight.

However, when compared to a similar shape, such as the comparison between the double and single glazed dome, EVT correlates well with T_{vis}. The single dome has a 12% greater visible transmittance and a 7% greater EVT. The structured polycarbonate glazing has a 40% greater visible transmittance than the fiberglass insulating panel and a 58% greater visible transmittance. Since the shape of the two skylights is similar, it is thought that the lower EVT for the fiberglass insulating panel pyramid is due to framing members inside each of the fiberglass insulating panels being opaque and not very reflective. As the incident angle increases, the transmittance of the assembly drops off rapidly.

Table 13: Comparison of Glazing T_{vis} and Skylight EVT

Skylight Code	Dim	Material	Shape	Tvis interior	Tvis average	EVT 3 ft well, sun 30 deg
C	4' x 4'	Single-glazed Acrylic	Dome	0.542	0.531	0.29
D	4' x 4'	Double-glazed Acrylic	Dome	0.505	0.474	0.27
E	4' x 4'	Double-glazed Prismatic Acrylic	Catenary Arch	0.671	0.713	0.22
G	4' x 4'	Structured Polycarbonate "Twinwall" Glazing	Pyramid	0.634	0.667	0.19
A	4' x 4'	Double-glazed Low-E glass	Flat - horiz.	0.467	0.459	0.15
F	4' x 4'	Fiberglass insulating panel	Pyramid	0.443	0.474	0.12
H	4' x 4'	Non-diffusing Bronze Acrylic	Pyramid	0.254	0.239	0.08

Thus the primary lesson to be gained from this comparison is that visible transmittance of glazing is important but so is skylight shape on the performance of the skylighting system. The bronze glazing, with the lowest visible transmittance, was also the poorest performer in terms of EVT.

CONCLUSIONS AND RECOMMENDATIONS

The primary observation from this study is that the effective visible transmittance of projecting skylights behaves markedly differently than that of flat horizontal glazing. Thus predicting the luminous performance of skylights requires a different model than the flat glass model typically used by many lighting and energy simulation programs. The data collected here can be used to generate curve fits of skylight effective visible transmittance (EVT) with respect to sun angle. At the very least, an estimate of a constant EVT with respect to incident angle for dome skylights is better than angle dependent EVT's developed for flat glazing.

Other conclusions from this study were:

- EVT's of skylights are reasonably proportional in most cases to the visible transmittance of the glazing *for the same skylight shape*.
- Rating of skylights should be performed at 30º solar elevation as over the course of a year in most US locations, the sun is most frequently at solar elevations close to 30º.
- Current ratings based upon light perpendicular to the skylight (90º elevation) or based solely on glazing properties do not provide the information needed to compare between skylights.
- Skylighting system effective visible light transmittance is the most important metric of skylighting system energy performance for mild climates such as in California.
- The EVT method of rating skylighting system overall transmittance is likely more robust than the photometric method as the EVT method can measure collimated light whereas the assumptions that underlie far field photometry are violated when the skylight is non-diffusing or light is otherwise collimated.
- This data can be used to generate better calculation tools for visible transmittance functions for projecting skylights. The SkyVision program from National Research Council Canada has made great progress in simulating the light transmittance of projecting skylights.
- The EVT data more accurately reflects the performance of skylight systems representative of those found in commercial buildings
- In the short term this research has validated the statement made in the IESNA Handbook[9] that the visible transmittance of dome skylights can be treated as constant overall wide range of incident angles.

[9] p. 8-11 (IESNA 200)

- There is a clear demarcation of haze tested according to ASTM D1003 between glazing materials that are considered diffusing versus those that are not. Haze values above 90% describe glazing materials that are essentially diffusing

The following statements about light well efficiency can also be made from the data collected

- The effective visible transmittances of skylighting systems diminish as skylight well depths increase
- Specular light wells are more effective at transmitting light than diffusely reflecting light wells.

Recommendations

This study has identified that projecting skylights of the same glazing visible light transmittance as flat skylights can provide significantly more light than flat skylights at sun angles normally encountered most of the year. Predictive models and rating systems need to incorporate skylight shape as a key variable. Since effective visible transmittance of the skylighting system has such a large impact on system performance the following recommendations are offered to improve the quality of information available to building designers.

- The methodology of the skylight EVT test should be codified into a an ASTM or NFRC test standard. Such a test method should be applicable to both diffusing and non-diffusing skylights as well as projecting and planar skylights. Such a test should yield results that can predict with high accuracy the transmittance of skylights at 30º solar elevation (60º incident angle). The EVT test described here was constrained by the necessity of measuring visible transmittance and solar heat gain coefficient simultaneously. Thus this method should be a starting point as accuracy is likely improved by some approximation of an integrating sphere. Such a test could be used to calibrate a skylight effective transmittance model based upon glazing properties and skylight shape.
- The National Fenestration Rating Council (NFRC) should develop a computer model to provide visible light transmittance ratings for projecting skylights and TDD’s (tubular daylighting devices). The SkyVision program, created by National Research Council Canada, was identified as having the features may well satisfy the criteria needed for rating skylights.
- The National Fenestration Rating Council (NFRC) should develop skylight visible transmittance ratings based upon light transmittance at 30º solar elevation. The sun positions encountered in most US locations over the course of a year are most frequently at solar elevations near 30º. The NFRC proposal for rating TDD’s at a 60º solar elevation should be revised so that the rating is based on 30º solar elevation.

- Energy and lighting simulation tools should be updated to account for skylight shape on the angular transmittance of the skylighting system.
- Energy simulation tools should be updated to calculate the well efficiency of diffuse and specular light wells. This is usually left to the designer to calculate off-line.
- Glazing haze values greater than 90% when measured in accordance with ASTM D1003 (notwithstanding the scope of D1003) be used as a definition of a diffusing glazing in energy codes and product specification until a better metric is developed.
- Further research should be conducted on metrics of diffusion. The current scope of ASTM D1003 limits haze measurements to materials that have haze values less than 30%. This limitation should be analyzed and potentially revised. Other methods of measuring diffusion of skylights and glazings should also be pursued.
- In the United States, the key repository of light well efficiency information is the *IESNA Handbook*. This information is in the form of a nomograph of well efficiency with respect to well cavity ratio (WCR) for various reflectances. This nomograph is valid for light wells with diffusely reflecting surfaces. As specular light wells are increasingly being used, it is recommended that the *IESNA Handbook* be updated to include well efficiency nomographs for tubular and square specular light wells.
- We hypothesize that long term skylighting system performance is affected by UV degradation of materials and the effect of dirt and dust build-up. It may be that the performance of highly transmitting systems are especially affected by aging and depreciation issues. It is recommended that on site surveys be conducted and detailed measurements be taken on the maintained effective visible transmittance of skylighting systems.
- Research should also be initiated on the effect of exterior and interior reflectors on the effective visible transmittance of skylights and their effect on the luminous distribution of light from the skylighting system.

GLOSSARY

Angular Transmittance
Is the visible light transmittance as a function of incident angle on the glazing.

Effective Visible Transmittance (EVT)
The ratio of the light transmitted through a skylighting system (skylight, light well diffusers etc.) to the light incident on the horizontal projection of the skylight opening.

Haze
Haze is ratio of diffusely transmitted light to the total transmitted light of a glazing. Haze is measured according to the procedures given in ASTM D1003-00.

Solar Heat Gain Coefficient (SHGC)
The SHGC is the fraction of incident solar radiation admitted through a material, either by direct transmittance, or by absorption and release into the interior space.

Tubular Daylighting Devices (TDD)
Also referred to as tubular skylights. Typically a round dome skylight mounted on top of a specular light well that is tube shaped. Usually there is a diffuser or lens at the base of the tubular light well.

Visible Light Transmittance (VLT)
Visible light transmittance refers to the fraction of light from the sun that passes through the product. Only light within the visible spectrum (between 360 and 800 nanometers) is considered in the measurement.

Well Efficiency (WE)
Well efficiency is the fraction of the light entering the top of the light well that exits the base of the light well.

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ASTM E903-96 *Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres*, American Society for Testing and Materials, West Conshocken, Pennsylvania.

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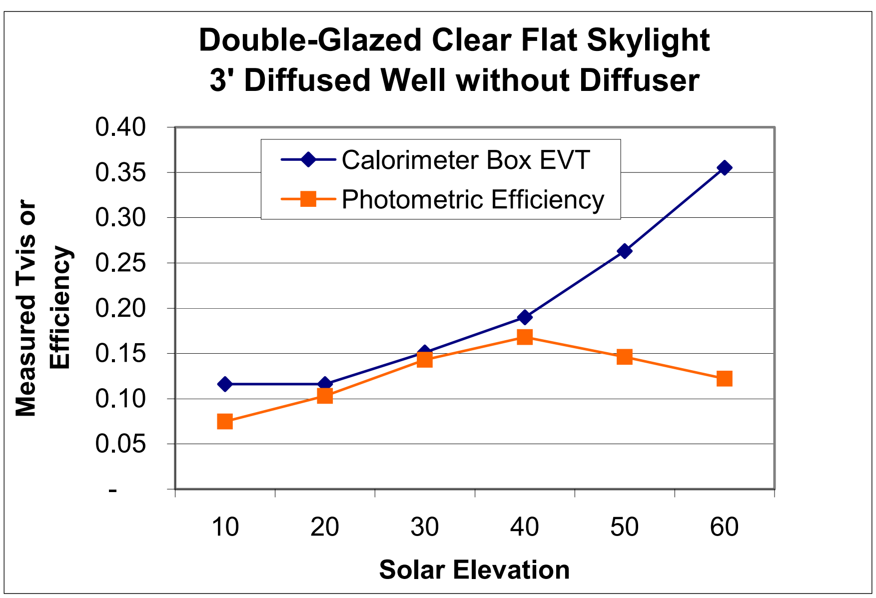
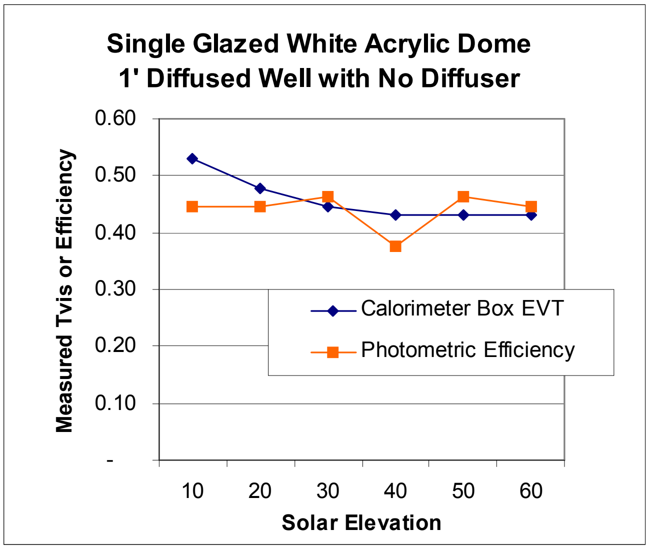
APPENDIX – ANGULAR EVT VS ANGULAR PHOTOMETRIC EFFICIENCY

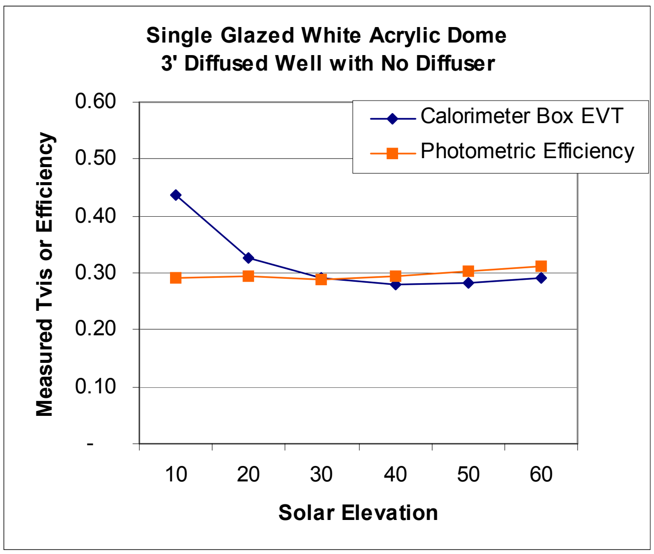
This appendix contains comparisons of the calorimeter box EVT and skylight photometric efficiency calculated from goniophotometric measurements for the range of angles that were available. Comparison of these measurements may provide insight into when either method might be expected to confirm the other method and when one can expect deviations.

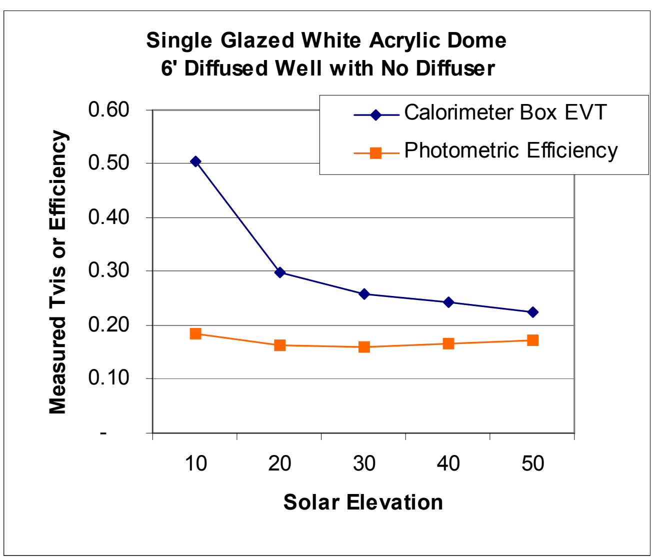
The first graph, that of a clear skylight over a 3 foot tall light well and with no bottom diffuser shows clearly the problems that result from apply photometric principles to a non-diffusing source. At low sun elevations, all the sunlight is reflected off of the diffusing white surfaces of the light well. At higher sun elevations, collimated light directly enters the room below the calorimeter and is registered by the calorimeter. Thus the EVT and photometric efficiency start to diverge.

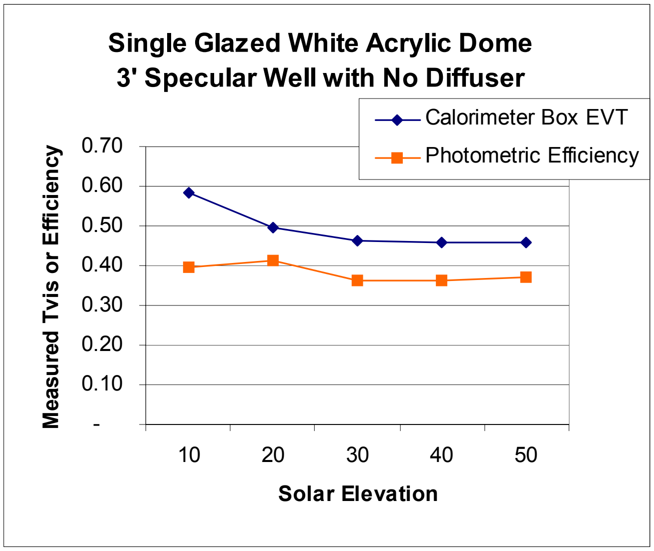
Since the solid angle represented by the sensors near the nadir are smaller than the solid angles higher up on the goniometric sphere, the luminous flux calculated by measurements at the bottom of the goniometric sphere are smaller than those on the sides. As the solar elevation increases and shafts of light are registered by these lower sensors, the photometric efficiency decreases. Since the distribution of light violates the assumptions underlying the photometric test method, the photometric efficiency results for a clear skylight are erroneous.

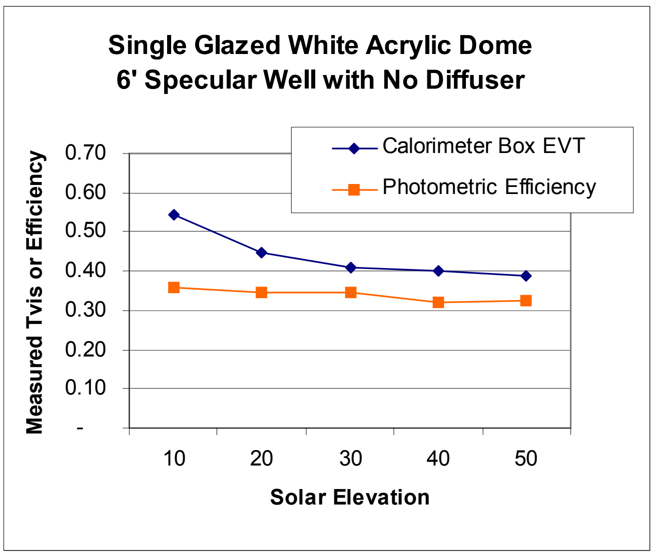


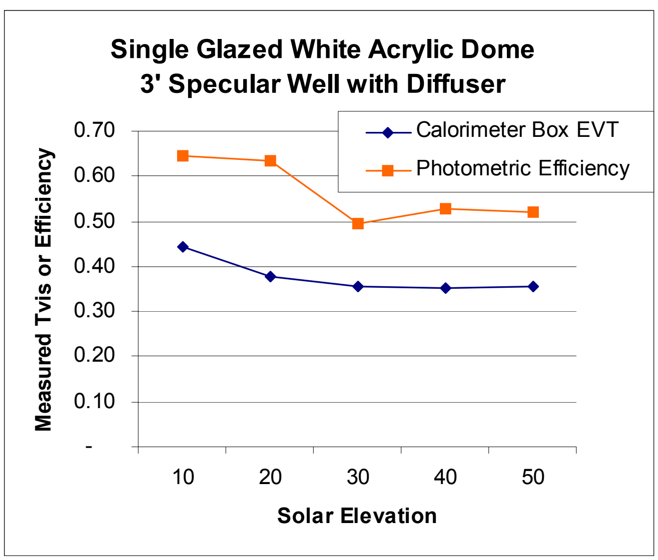

Single Glazed White Acrylic Dome
1' Diffused Well with No Diffuser
Measured Tvis or Efficiency
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
60
Solar Elevation
Calorimeter Box EVT
Photometric Efficiency

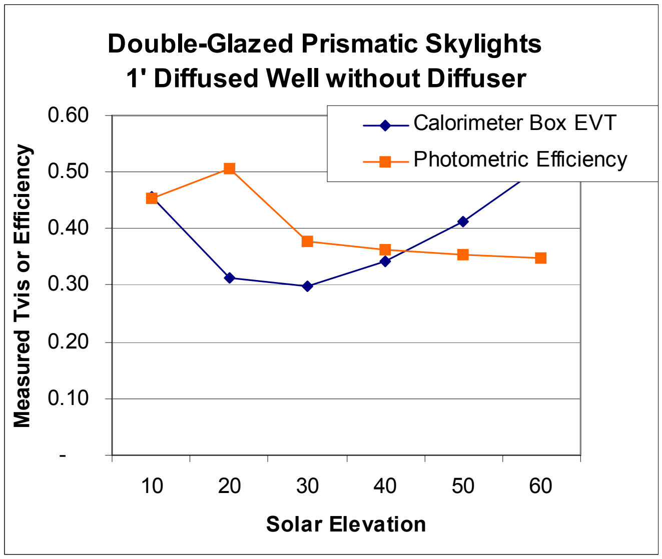

Single Glazed White Acrylic Dome
3' Diffused Well with No Diffuser
Measured Tvis or Efficiency
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
60
Solar Elevation
Calorimeter Box EVT
Photometric Efficiency

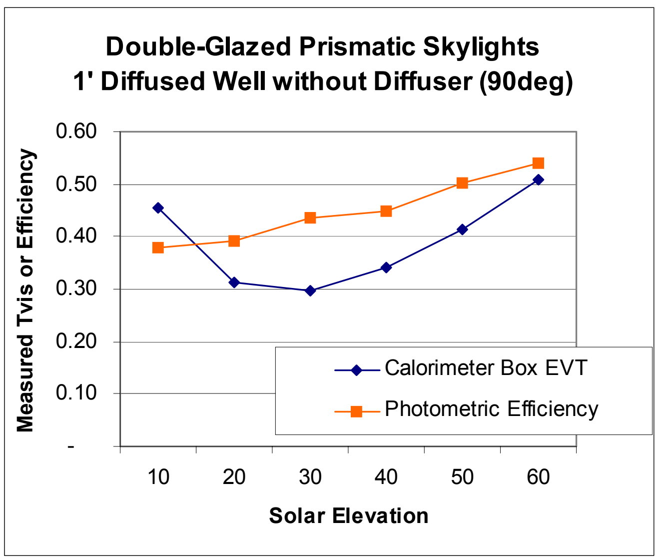

Single Glazed White Acrylic Dome
6' Diffused Well with No Diffuser
Measured Tvis or Efficiency
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
Solar Elevation
Calorimeter Box EVT
Photometric Efficiency

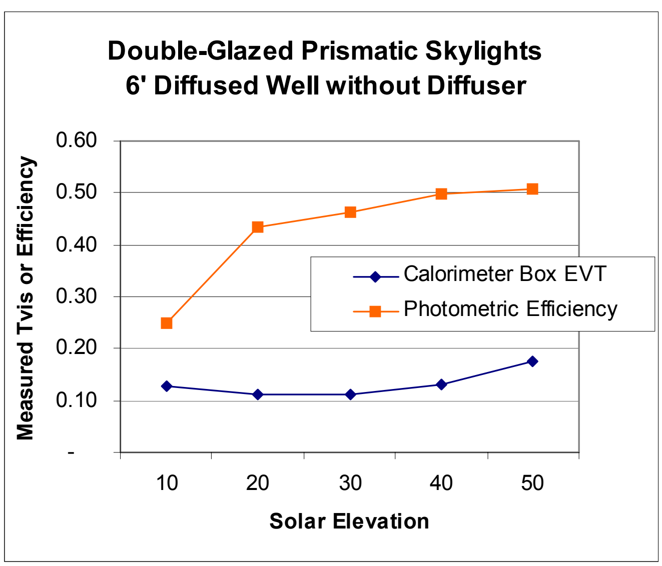

Single Glazed White Acrylic Dome
3' Specular Well with No Diffuser
Calorimeter Box EVT
Photometric Efficiency
Measured Tvis or Efficiency
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
Solar Elevation

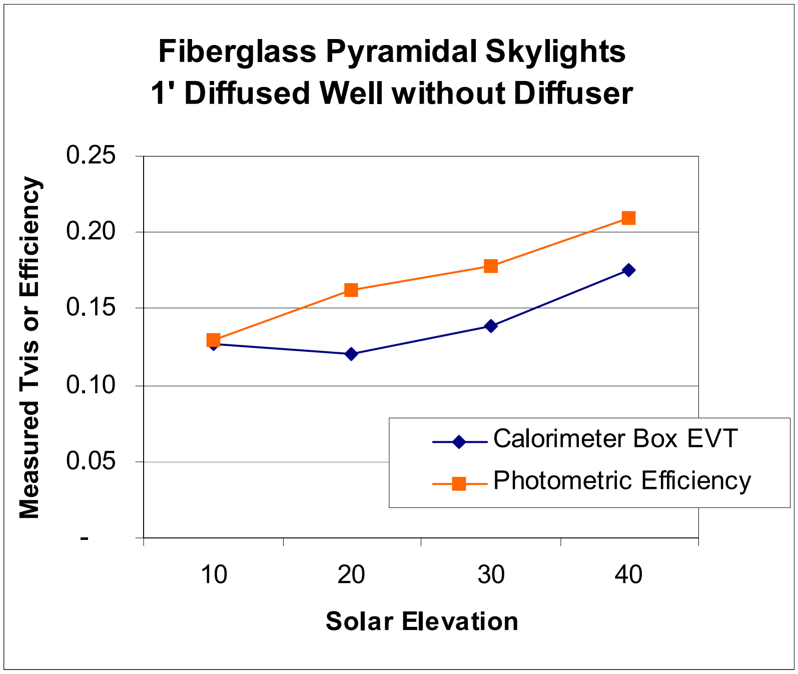

Single Glazed White Acrylic Dome
6' Specular Well with No Diffuser
Calorimeter Box EVT
Photometric Efficiency
Measured Tvis or Efficiency
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
Solar Elevation

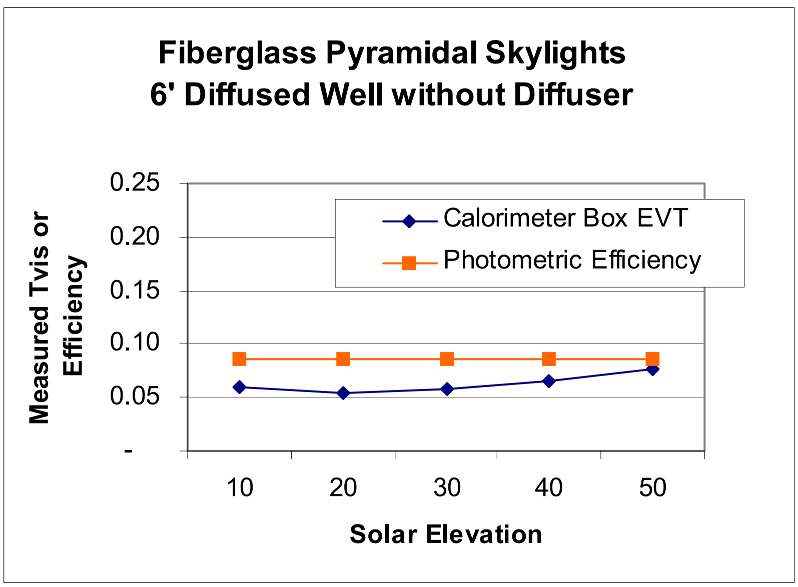

Single Glazed White Acrylic Dome
3' Specular Well with Diffuser
Calorimeter Box EVT
Photometric Efficiency
Measured Tvis or Efficiency
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
Solar Elevation


Double-Glazed Prismatic Skylights
1' Diffused Well without Diffuser
Measured Tvis or Efficiency
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
60
Solar Elevation
Calorimeter Box EVT
Photometric Efficiency


Double-Glazed Prismatic Skylights
1' Diffused Well without Diffuser (90deg)
Measured Tvis or Efficiency
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
60
Solar Elevation
Calorimeter Box EVT
Photometric Efficiency


Double-Glazed Prismatic Skylights
6' Diffused Well without Diffuser
Measured Tvis or Efficiency
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
Solar Elevation
Calorimeter Box EVT
Photometric Efficiency


Fiberglass Pyramidal Skylights
1' Diffused Well without Diffuser
Measured Tvis or Efficiency
0.25
0.20
0.15
0.10
0.05
-
10
20
30
40
Solar Elevation
Calorimeter Box EVT
Photometric Efficiency


Fiberglass Pyramidal Skylights
6' Diffused Well without Diffuser
Measured Tvis or Efficiency
0.25
0.20
0.15
0.10
0.05
-
10
20
30
40
50
Solar Elevation
Calorimeter Box EVT
Photometric Efficiency